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PROTECTION OF NONMETALLIC AIRCRAFT FROM LIGHTNING

III - ELECTRICAL EFFECTS IN GLIDER TOWLINES

High Voltage Laboratory
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NACA

WASHINGTON

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SUMMARY

A glider tow operating in or near a thunderstorm is exposed to three distinct types of electrical hazard:

A direct lightning stroke may enter at one of the aircraft, pass along the towline, and leave from the other aircraft. The chance of this occurring is decidedly greater than the probability that an isolated airplane will be struck. If a textile towrope is used, the lightning current will pass as an arc in the air near the rope, but the likelihood that the rope will be seriously damaged is rather slight, particularly if the rope is protected by suitable metal arcing rings at the two ends. If a metal towrope is used, the current will flow in it, but will not damage it provided the cable diameter exceeds 0.14 inch.

A lightning stroke may pass directly to some intermediate point on the towline. Such a stroke might sever a single metal cable unless its diameter is greater than 0.35 inch (an undesirably heavy line). The use of a lighter metal core protected by a layer of insulation and an outer metal braid gives a lighter and more arc-resistant construction, and also gives the possibility of two-wire telephonic communication between the aircraft. The tendency for the point of contact to be blown along the cable may be enough to prevent the severing of even a lighter metal cable. Textile rope appears to be immune to such a direct hit, except perhaps under very rare conditions.

Even if no lightning stroke occurs, an electric current of appreciable magnitude will flow in the towline all the time the tow is within a few miles of the thunderstorm. This current will not harm a metal cable but may be very damaging to a textile rope. In this report a basis is worked out for making quantitative estimates of the hazard from such towline currents for any assumed

combinations of storm intensity and cable resistance. If the rope could be covered with a nonporous, waterproof, elastic insulating "skin" which would keep it insulating under all conditions, this would provide a preferable solution to the problem, but no such coating has yet been found. The most successful preventive measure thus far tried is to impregnate the rope with colloidal graphite (aquadag) so that it will remain, under all conditions, a sufficiently good electrical conductor to carry this current without being overheated. Further measurements should be made on the electrical and thermal properties of nylon ropes, made conducting under factory conditions.

I. INTRODUCTION

When a glider tow is operating in or near a thunderstorm the craft are subjected to a rather intense field which will cause a number of electrical effects, some of which - such as burning of the towrope - may prove disastrous. It is the purpose of this report to present a comprehensive picture of the various possibilities, to estimate the various hazards as definitely as possible in the light of the rather meager information available, to report the results of experiments devised to supplement this information, and to suggest means for reducing these hazards from thunderstorms.

The most obvious effect to be expected is that the tow may be struck by lightning. The records of the NACA Subcommittee on Lightning Hazards to Aircraft show that lightning strokes to single aircraft are by no means rare occurrences, and that larger and faster aircraft are more often struck than smaller ones. This suggests that, at least to some extent, the distortion of the electric field of the thunderstorm by the presence of even an isolated aircraft has a triggering action and may initiate a stroke which would not have occurred if the aircraft had been absent. The length of the usual towline is very much greater than the wing span of any aircraft, and the triggering action must be correspondingly greater. Hence in the operation of glider tows in thunderstorm regions the occurrence of a lightning stroke to one of the aircraft and thence through the towline to the other craft and to ground or cloud must be anticipated. Present types of all-metal airplanes are practically immune to serious damage from lightning, and it is the main purpose of the present investigation to develop methods for giving similar protection to nonmetallic craft. This particular report, however, is concerned only with the effects on the towline itself, and with methods for making it immune to damage from heating and burning under such conditions.

A similar and more dangerous but much less probable event is the occurrence of a lightning stroke from the thundercloud directly to some point on the towline, from which the current will pass to the craft at either end, or (perhaps) to some other point on the towline, before continuing to ground. The localized burning at the point where the arc strikes a metal towline will be much more severe than the uniform heating produced by the passage of current along the full length of the line. Hence a cable which will withstand this arcing will be amply sufficient to survive the type of stroke described in the preceding paragraph.

Still another effect which is certain to occur much more frequently than the two just mentioned, and which is hardly less dangerous, is the flow of a small current in the towline, and the corresponding development of corona discharge (St. Elmo's fire) at the extremities of the aircraft and on the towline. Such currents, though small, last for a considerable time and may be very destructive to unprotected textile ropes. They would, however, do no harm to metal ropes, though they may seriously interfere with radio communication. Such currents will occur in textile towlines unless the towlines remain highly insulating. This favorable condition might exist during a sustained flight well above the freezing isothorm, but unfortunately the insulating value of a textile towline is certain to be destroyed by the accumulation of moisture when flying for even a short distance through a cloud of water droplets.

II. SYMBOLS

a equivalent radius of aircraft (i.e., 1/2 wing span)

B constant in equation (A18)

b radius of wire, or towline

C constant of integration

c radius of outer cylinder

d distance point to plane

d_m distance to point of maximum potential

E voltage

E_c voltage drop in corona (out to $r = r_c$)

g voltage gradient

g_o voltage gradient due to clouds, undisturbed by tow

g_c critical voltage gradient at which ionization by collision begins

I current in towline

i corona current leaving wire per unit length

k coefficient giving current per unit of $(\text{voltage})^2$

l half-length of towline

Q electric charge induced on aircraft

q volume density of space charge

R resistance per unit length of towline

r radius

r_c outer radius of corona

r_m radius at which two components of g are equal

u ionic mobility

V potential (usually with respect to midpoint of tow)

v velocity

x distance along axis of tow

z a variable $= g^2$

III. DIRECT STROKES TO AIRCRAFT

To estimate the effect of a lightning stroke on a towline when the lightning current passes through it from one aircraft to the other, it is essential to have a knowledge of the probable magnitude and duration of the lightning current and of the electrical resistivity, cross section, and other properties of the towline. Fortunately there has been a very active experimental study of lightning during the past two decades because of its importance in connection with the protection of electric transmission lines. The very complex sequence of events which form a lightning stroke has been studied in detail by Schonland (reference 1) and his colleagues, using the Boys high-speed camera. The location and magnitudes of charge centers in thunderclouds have been studied by Workman (references 2 and 3) in New Mexico and by Simpson (reference 4) in England. Quantitative data on the current in the stroke have been published by McEachron (reference 5), Wagner (reference 6), and others. A convenient summary of such data is available in a paper by Wagner and McCann. (See reference 7.) These studies show that a typical lightning stroke consists of a preliminary "leader" which carries a relatively small current and which is immediately followed by one or more pulses during which the current rises to a very high value for a few hundred-thousandths of a second. Between and following these current peaks the current may continue at a much lower value for several hundredths or even tenths of a second. The median value (i.e., that exceeded in only 50 percent of the cases) for the crest current is about 30,000 amperes, and the median duration of the peak (down to half value) is 30 microseconds. The electric charge transferred in any one peak is thus about 1 coulomb. However, the median value of total charge for a complete stroke is about 30 coulombs; hence it is evident that the greater part of the charge is carried by the low-current (100 to 1000 amperes) part of the stroke between the peaks.

For the present purpose towlines fall into one or the other of two classes: Either they are of metal, in which case even a very thin cable will have an electrical resistance of less than 0.001 ohm per centimeter, or else they are of textile fiber (usually nylon), which, even when wet or when treated so as to be conducting, will have a resistance greater than 100 ohms per centimeter.

In the former case the current will flow entirely in the metal and develop heat at a rate proportional to the resistance per unit length and to the square of the instantaneous value of the current. The total heat developed by a single current pulse is thus proportional to $\int i^2 dt$. Data in reference 5 indicate a median value of 10,000 amperes squared-seconds as a reasonable approximation for this quantity. For steel cable with a resistivity of 20 microhm-centimeters, a density of 7.8, and a specific heat of 0.12, a temperature rise of 100° C would be obtained with a discharge of 200,000 amperes squared-seconds if the cable had a cross section of only 0.1 square centimeter (i.e., a diam. of 0.14 in.). This is probably smaller cable than is likely to be used. A temperature rise of at least 300° C, moreover, would not materially reduce the tensile strength of the cable, and hence could be tolerated. A more complete treatment of the surge-current-carrying capacity of metallic conductors with numerical values for other metals will be found in part II of this series. (See reference 8.) The foregoing theoretical deduction is corroborated by the fact that in many cases steel rural telephone wires only 0.1 inch in diameter have been struck by lightning without being fused, except at the point of contact with the arc. Further confirmation is found in laboratory experiments using an oscillating surge current which had a value for $\int i^2 dt$ of 5250 amperes squared-seconds. Computations similar to those used previously show that this value of $\int i^2 dt$ should be just sufficient to fuse a No. 26 copper wire. In the experiments No. 25 was found to be unmelted, No. 26 fused to drops of liquid metal, while No. 27 was mostly vaporized. It may therefore be concluded that if a metal towline is used of sufficient section to give the required mechanical strength, there is practically no danger that it may be melted by a lightning stroke which passes through the whole length of the tow from one aircraft to the other.

In the case of a textile rope, the resistance is so high that at a current of only a few hundred amperes the voltage gradient along the rope will become greater than the value (about 30,000 volts per cm) at which air at atmospheric pressure breaks down and permits the passage of a spark. Hence the first current peak is practically certain to initiate an arc alongside the rope and the bulk of the current will flow in this arc during the rest of the discharge.

A number of trials were made in the laboratory in an effort to imitate various phases of such a flashover. Thus figure 1 shows a transient arc of 25,000 amperes crest ($\int i^2dt$ = 5250 (amperes)^2-sec) playing along a cotton sash cord which had been soaked in tap water. The cord showed no appreciable damage after the discharge. In some trials a 1000-ampere surge was used to trigger a discharge across a short gap, and was followed up by a current of about 30 amperes lasting for 1 second, supplied by a 1000-volt direct-current generator. With this duration the arc passes the same charge as a median stroke of natural lightning. The arc flame spreads over a considerable area but its terminals are fixed by the metal electrodes. In other experiments a 60-cycle alternating-current arc was passed between electrodes attached to the rope by the flashover of a transformer initially energized to about 200 kilovolts applied to a rod gap about 22 inches long connected in series with the specimen. The arc current was limited by the equipment available to an initial rush of 12 amperes (effective value) which soon decreased to 4 amperes. By leaving the circuit closed for 7.5 seconds the total effective ampere-seconds could be made equal to the median lightning value of 30 ampere-seconds. The duration of the latter is, however, seldom longer than one- or two-tenths of a second, while the current is correspondingly greater. The thermal conductivity of a textile rope is so low that there is probably little diffusion of heat into it even in the 7.5 seconds, so that in this respect the two cases may be comparable. However, there was time for the arc to move about even more than in the direct-current tests, so that the heating was not as concentrated in space as if the arc had been stationary. In an effort to minimize this motion of the arc, the rope was placed in a vertical position for the alternating-current tests, and the terminal of most importance was put at the lower end.

In an actual flight the relative motion of the towline and the air will surely cause the arc to flow away from the line very rapidly, and even in the few tenths of a second of a long lightning stroke the arc might shift by several feet. At the ends, where the towline is attached to the aircraft, the arc will be constrained to remain close to the rope; and hence it would be expected that the damage would be greatest at these points. In view of the foregoing, it is somewhat questionable whether these trials simulate actual conditions closely enough to be very significant. Typical results are given for whatever they may be worth.

Figure 2 shows a 4-ampere alternating-current arc flashing over a dry, untreated 13/16-inch nylon rope, the lower electrode being a metallic thimble of the usual type. The tendency of the arc to drift away except at the thimble is very marked even in the quiet air of the laboratory. Figure 3 shows the scorching and melting of the surface near the thimble after 7.5 seconds of exposure. Figures 4 and 5 show a similar 3-ampere alternating-current arc over a shorter length (15 cm) of nylon rope which had been rendered conducting (2000 ohms per cm) with aquadag. The surface damage after 10 seconds exposure and the shape of the electrodes are shown in figure 6. A 30-ampere direct-current arc lasting 1 second is shown in figure 7. The scorching of the untreated nylon and the location of the electrode in this experiment are shown in figure 8. The damage in this case seems to be less, although the current was greater in the same proportion as the time was shorter. This suggests that lightning with still shorter time but still larger current may be still less destructive.

As the most damage occurred near the electrodes where the arc was constrained to remain near the rope, an obvious remedy is the use of an arcing ring. Such a ring of 1/4-inch diameter copper tubing supported about 1/2 inch away from the rope was tried with untreated nylon, and also with aquadag-treated nylon. The beneficial effect of the arcing ring in causing the arc to terminate at a distance from the rope is evident in figures 9 and 10 for the two specimens, respectively. After the discharge neither specimen showed any visible signs of appreciable damage.

To the extent that the conditions present in these trials are similar to those occurring in flight, the results indicate that the risk of damage to a textile towline from a lightning stroke to the aircraft at either end is slight. Even this slight hazard can be materially reduced by providing the metal fittings at the ends of the line with arcing rings, separated from the rope.

IV. DIRECT STROKE TO THE TOWLINE

A. DAMAGE TO METAL CABLE

The second and probably more serious effect is the melting which occurs when there is a direct stroke to a metal towline. This melting is caused by the intense local heating at the point of contact of the stroke with the towline, and is a direct result of the well-known voltage drop (cathode - or anode) in an electric arc where the current enters or leaves the surface of a conducting electrode. In most cases this electrode drop amounts to from 6 to 8 volts (reference 9) and is concentrated in a very small fraction of an inch of the arc path adjacent to the electrode. The amount of heat developed, and hence, in a rough way, the amount of melting produced, is therefore proportional to the first power of the current and to its duration. Hence it is proportional to the total quantity of electricity passed by the stroke. The greater part of this quantity flows in the moderate current which persists during the relatively long intervals between successive high-current peaks.

A rough estimate of the danger resulting from such an occurrence can be obtained by taking the figure of 2 coulombs (equivalent to 2 amperes flowing for 1 sec) per cubic millimeter found experimentally for copper and brass electrodes, by Bellaschi, and combining it with the value of 140 coulombs for the quantity of electricity discharged. This corresponds to a severe stroke and would be exceeded by only 5 percent of observed lightning strokes. This indicates that the volume of fused metal is not likely to exceed 70 cubic millimeters. This is the volume of a sphere 0.5 centimeter (0.2 in.) in diameter. The rise in temperature would doubtless weaken the material adjacent to the melted portion, so that the cable diameter should be larger than 0.2 inch by a considerable factor. Experience with the overhead ground wires which are widely used to protect high-voltage transmission lines from lightning indicates that steel cables about 3/8 inch in diameter are satisfactory for intercepting lightning arcs.

This line of argument seems to indicate that to insure safety positively a cable should be used which is probably somewhat heavier and stronger than would otherwise be needed for towing gliders. However, several other factors should be considered which tend to ameliorate the situation. Among these are (1) the tendency of the arc to move along the wire so that the heating will not be confined to one spot, (2) the relatively remote probability of a stroke direct to the towline, and (3) the possibility of protecting a light, metal cable by an outer coating. These will be discussed in turn.

The more powerful strokes - that is, those which release charges as great as the 140 coulombs assumed above - are almost always multiple in character and have a duration of several hundredths or even tenths of a second. An airplane traveling at 120 miles per hour moves about 50 centimeters (1.5 ft) in each one-hundredth of a second. Hence, if the arc were fixed in the air, the motion of the cable would spread the heating over this length. Furthermore, the magnetic field produced by the current exerts a force on the arc tending to move it. This tendency is so strong that even in laboratory experiments with arcs to the side of a wire it has been found essential to keep the distribution of current, and the arrangement of the conductors which carry it, very symmetrical if the arc is to remain at all fixed. In a typical case even with such an arrangement, it was found that the terminus of the arc wandered about in the course of 1 second over a track 35 centimeters long. An examination of metal airplanes which have been struck by lightning often shows a succession of small pits which indicates a relative motion of the arc and the metal. (See reference 10.)

B. PROBABILITY OF A DIRECT HIT TO A TOWLINE

The probability that a stroke will pass directly to the towline in preference to the aircraft at its ends is surely rather small, but is difficult to estimate. As shown by Workman (references 2 and 3), some storms show many strokes which pass from cloud to ground and are therefore approximately vertical; while in other storms nearly all strokes are from cloud to cloud and are, for the most part, nearly horizontal.

To get a rough indication of the probabilities involved, a series of model experiments were made on a scale of approximately 1:1000 by passing sparks from a 2-million-volt surge generator to a model tow. The charge centers in the clouds were simulated by the tips of two vertical rod electrodes 8 feet apart. The towline was simulated by a No. 20 straight copper wire 8 inches long, to each end of which was attached a small piece of flat sheet copper cut in the outline of an airplane. The wing spread of each outline was $1\frac{1}{2}$ inches and its length, nose to tail, 1 inch.

In trials with the electrode tips in the vertical plane passing through the towline, it was found that if the line joining the electrodes bisected the towline and made an angle of less than 5° with the vertical, at least one terminal of the discharge was on the towline in 50 percent of the trials, although in all but one case the other terminal was on one of the aircraft. Figure 11 shows simultaneous photographs taken by two cameras aimed at right angles to each other of a discharge which hit the model towline and the left wing tip of the towing plane. If the line joining the electrodes made an angle with the vertical exceeding 20°, all sparks struck to the aircraft.

A second set of trials was made to simulate a horizontal stroke between cloud centers in the same horizontal plane as the aircraft and on opposite sides of the tow. It was found that all sparks passed to the wing tips of the sheet copper models even when the line joining the electrodes was perpendicular to and centered on the towline.

A third set of trials was made with the line joining the electrodes vertical, but displaced to one side of the towline which was horizontal. When the displacement was 8 inches (one-twelfth the electrode spacing) or more, all the sparks missed the tow. For smaller offsets the number of hits to the towline was on the average the same as if all those strokes were hits for which the offset was less than one-eightieth of the electrode spacing.

To pass from these experiments on a small model to an actual thunderstorm involves many questionable assumptions as well as an extrapolation by a factor of 1000 in the dimensions. Therefore too much weight should not be assigned to any conclusions deduced from them. However, they seem to indicate that the chances of a direct hit to the towline itself are rather small. Perhaps there is one chance in 2000 of such a hit for each passage of a tow through an average small thunderstorm.

C. USE OF TWO-CONDUCTOR LINES

In case it is desired to maintain telephone communication between tow plane and glider, a very promising type of construction would be to use as the towline a steel cable of sufficient mechanical strength to carry the load, and to cover it first with a layer of electrical insulation and then with a thin metallic braid. This provides the two conductors needed for a shielded communication line and has the further advantage that in case of a direct lightning stroke the outer layers will protect the mechanical strength of the inner cable. A number of tests have indicated that a 1/8-inch steel cable coated with a layer of cellulose tape only 0.008 inch thick and covered with braided copper shielding equivalent in conductivity to a No. 14 copper wire, showed no signs of damage after being subjected to a 35-coulomb arc while loaded to a tension of 600 pounds. With such a construction the arc passes to the outer metal, which may be badly damaged (see fig. 12) while the inner conductor is only slightly, if at all, affected by the arc. Thus the inner cable is protected and should be the member to be relied on for mechanical strength.

Trials with only the insulating layer over the inner conductor gave unsatisfactory results. The voltage was, of course, ample to puncture the insulation, and the presence of the insulation tended to keep the arc at one spot and thus to concentrate the heating.

D. HITS TO TEXTILE ROPES

In the case of a direct hit to a textile rope it seems probable that the arc will for the most part pass entirely in the air over the surface of the rope, but that the concentrated heating at the electrode surface which injures a metal cable will be absent. On the other hand, the textile is much more affected by a small rise in temperature than is the metal.

Experiments on this point were made with the same alternating-current circuit mentioned in section III. The arc passed from a 1/8-inch metal rod placed 1/2 inch from the surface of the rope, and after rising along the rope terminated on a metal tube which surrounded the rope about 10 inches above. The trials were made with 13/16-inch nylon rope which had been treated with aquadag. One sample, A, had a resistance of about 2000 ohms per centimeter, while the other, B, had 200 ohms per centimeter. Figure 13 shows the 3-ampere arc passing close to sample A. During the 14 seconds that voltage was applied, the arc ceased and restruck three times. The damage is shown in figure 14. It is seen that the result is no worse than when the arc occurred between metal electrodes attached to the rope, and that there is little indication that any considerable part of the current passes to the rope and develops a cathode hot spot. Figure 15 shows similar surface melting on the low-resistance sample, B, after a 3-ampere arc had struck and restruck five times during a 15-second exposure.

It would appear from the foregoing that a direct stroke to a textile towline would not involve any hazard greater than that of a lightning stroke to the aircraft.

One very remote possibility should, however, be mentioned. Occasionally (reference 5, p. 175) lightning strokes have been observed which do not start with the usual high-current surge, but instead build up gradually to a few hundred amperes. It is conceivable that if the rope has a resistance as low as 100 ohms per centimeter, the longitudinal voltage gradient may not be enough to produce a flashover in the air outside of the rope. In this case the heat developed in the rope would be very great and it would be melted in a fraction of a second. However, in the trial the results of which are shown in figure 15 the sample had only 200 ohms per centimeter, and the first surge of current recorded by the magnetic oscillograph was only 12 amperes; yet the specimen arced over and was not seriously damaged. Of course, the flashover of the series rod gap in this experiment may have caused a preliminary surge of considerably greater crest current. In flight the capacitance of the aircraft might have a similar effect.

V. CORONA CURRENTS IN TOWLINE

A. GENERAL PHENOMENA

The third electrical effect is the flow of current in the towline as a result of that component of the electric potential gradient of the storm which is in the direction of flight of the tow. Such a current is present at all times while the tow is operating in the neighborhood of charged thunderclouds, whether lightning strokes occur or not. The current enters and leaves by brush or corona discharges (St. Elmo's fire) which occur both at the extremities (nose, wing tips, etc.) of the aircraft and along most of the towline itself, except for the ends which are shielded by the aircraft and a neutral zone near the center which is uncharged. These corona currents are small and are conveniently measured in milliamperes. They will produce absolutely no damage to a metal towline, but even a small current when forced through the high resistance offered by a textile rope will develop heat and cause the rope to burn (or melt if of nylon). The charred and carbonized residues are better conductors and permit an increase in the current. The destructive action is thus cumulative, and only a few minutes are required to destroy the strength of the rope. Figure 16 is a photograph taken in a darkened room of a cotton rope about 20 feet long carrying 6 milliamperes. The light comes from burning fibers and partly from local arcs. The current had been flowing for about 2 minutes before the photograph was taken, and the rope broke of its own weight 3 minutes later.

The electrical relations existing where the tow is flying in the electric field of a thunderstorm can be understood by reference to figure 17. Here is shown a tow flying in the uniform electric field between a large, positively charged cloud at the right and a negatively charged cloud at the left. The approximate positions of some of the equipotential surfaces have been sketched in. The values of potential relative to the center point of the towline are indicated on the basis of a uniform field gradient of 300 volts per centimeter in the absence of the tow. The resistance of the towline has been assumed to be small. Figure 18 shows in more detail for one quadrant the approximate distribution of potential to be expected. For a towline of high resistance the distortion of the field would be somewhat less, and for other relations between the direction of flight and the direction of the electric field, the shape of the equipotential surfaces would be different, but the essential features would still be similar to those indicated in figure 17.

The crux of the glider-rope problem lies in the quantitative estimation of the probable magnitude and duration of the towline current. It is evident that the potential difference causing this current (i.e., corona current) to flow is obtained by multiplying the existing thunderstorm gradient g_0 by the length $2l$ of the towline. The limitation on the current arises in part from the resistance of the towline, and in part from the inability of the corona at the extremities of the line and of the aircraft to discharge more than the particular value of current which corresponds to the voltage acting. The current in the central portion of the towline is, of course, at all times, except for minor transient effects, equal to the sum of the corona current from either aircraft and that which leaves from the surface of half the towline.

In analyzing the situation considerable simplification can be obtained by recognizing the very different orders of magnitude of the various dimensions involved. The clouds and the distances between the charge centers within them are to be measured in miles (10^5 cm). The length of the tow is some hundreds of feet (10^4 cm). Hence the undisturbed voltage gradient varies only a few percent in a distance comparable to the length of the tow; although when regarded on the larger scale of the clouds, the gradient appears to be far from uniform. The wing span or the length of the aircraft is of the order of several tens of feet (10^3 cm), so that at points as distant from it as the center of the towline, the effect of a charge located on the airplane is about the same as that of the same charge concentrated at a point or sphere at the center of the aircraft. Also the effect at the glider of a charge on the tow plane is relatively small and vice versa. The radii of curvature of the edges and corners of the airfoils are of the order of a few inches (10 cm) at most, so that each corner forms a more or less isolated point, the corona discharge from which is but little affected by the presence of the others which are some feet away.

In figure 17 the equipotential surface ABD which, in the undisturbed field would have passed through D, is bent out to B. This distortion is probably not very different from that produced when a sphere of radius a (where a is roughly half the wing span) is kept at the potential of the center of the towline. In this case, as shown in section V B 2c, the distance DB becomes equal to $\sqrt{al}$ and will be of the order of 3×10^3 centimeters. If the resistance of the cable is high, the field distortion and the distance DB will be correspondingly less. However, a reasonable basis for estimating the value of corona current discharged would appear to be (1) to consider each aircraft as an assemblage of "point-plane" gaps of spacing DB maintained at the voltage E given by

$$E = g_0 l - RIl \tag{1}$$

where R is the resistance per unit length of the towline, and (2) to consider that each element of length of the towline is subjected to a voltage which tends to produce corona and which is proportional to, though less than, E.

B. DIAGRAMMATIC REPRESENTATION

A convenient graphical representation of the relations involved is shown in figure 19. Here there is plotted as ordinate the total current flowing in the towline at the center of its length, or in the corona discharges at either end. Voltages measured from the center of the towline are plotted as abscissas. (It is tacitly assumed that the current-voltage characteristic is the same for the tow plane as for the glider, and also that it is the same for both polarities. The errors resulting from these assumptions are probably small compared to those from other sources.)

The curve ECDK (the evaluation of which will be discussed in sec. V B2) is the current-voltage characteristic of the aircraft and cable, and represents the relation between the total corona current and the voltage between the aircraft and the distant equipotential surface ABC of figure 17. As a measure of the intensity of the storm, and of the location and orientation of the tow with respect to it, and thus of the exposure to hazard, the voltage $(g_0 l)$ spanned by half the tow length may be taken. For a particular case with $l = 100$ meters and $g_0 = 750$ volts per centimeter, the result is $g_0 l = 7500$ kilovolts, and in figure 19 is drawn the vertical "storm exposure line" AB at this abscissa. This intersects curve ECDK at K and indicates that the maximum towline current for a cable of zero resistance and such a storm condition is the ordinate of K (viz, 430 ma). For a towline of specified resistance, as, for example, 10,000 ohms per centimeter, a line such as AC, for which the ratio of AG in volts to GC in amperes is equal to 10,000 times the half tow length l in centimeters, can be drawn. This "resistance line" intersects the corona characteristic line at C and indicates by CG that the corona current for this case is 37 milliamperes. The resistance drop in half the towline as shown by AG is 4300 kilovolts and the balance of the voltage which is available to produce corona is shown by CG to be 3700 kilovolts. A steeper line such as AD corresponds to a towline of lower resistance (100 ohms per cm).

Of the three types of information needed for the quantitative construction of a diagram such as figure 19, the easiest to obtain is the resistance of the towline. This can be measured with conventional electrical instruments or by noting the current which flows when a known fairly high voltage is applied to a specimen of rope. Ohm's law is obeyed, at least approximately, except when the voltage gradient is so high that local sparking is taking place and the rope is on the verge of failure. Table 1 gives values of resistance measured at gradients of about 1000 volts per foot on a number of different ropes under various conditions.

1. Storm Exposure Line

The location OA of the "storm exposure lines" such as AB, or A'B', is proportional to half the length of the towline and to the component of the electric field gradient in the direction of flight. The first factor is known, while the second factor varies from zero when the tow is remote from the storm to a maximum which certainly often exceeds 500 volts per centimeter and which may even approach an upper limit of 10,000 volts per centimeter. This limit was found by Macky (reference 11) to be the gradient at which water drops suspended in air become unstable and initiate spark-over. Workman (reference 3) gives typical experimental results showing that the horizontal component of gradient exceeds 300 volts per centimeter throughout regions of perhaps 60 cubic kilometers and that it exceeds 100 volts per centimeter throughout a volume ten times as great. As a typical example of what may be expected, figure 20 shows the characteristic storm condition described by Workman. (See fig. 16b of reference 3.) Here two charge centers, each with 33 coulombs, are located at heights of 6 kilometers and 5 kilometers above the ground, with a horzontal distance of 3 kilometers between them. This arrangement is indicated in the lower part of figure 20, which also shows two typical flight paths AA' and BB' through the storm. These flight paths miss the center of the upper charge by distances of 1 kilometer and 2 kilometers, respectively. The graphs of gradient have been computed for paths directly above the storm centers as shown, but substantially the same gradients would be encountered on flight paths which passed at the same distances to one side of the charge centers. The curves of towline current were derived from those of gradients on the basis of a low resistance towline and the corona current curve ECDK of figure 19. At the points marked "a" in figure 20, the conditions correspond to storm exposure line AB of figure 19, while at points marked "b" conditions correspond to line A'B'. At points marked "c" conditions correspond to line A'B' of figure 33.

The upper curves, for flight path BB' show that the current may be well over 10 milliamperes for nearly a minute even if the flight avoids the nearest charge center by as much as 2 kilometers. Most storms are more complex than the simple type shown in figure 20 and the duration of the exposure would be correspondingly longer. With a closer approach to the charge centers, as on path AA', the peak currents are very much greater. The indicated peak value of 2.5 amperes would probably destroy any textile rope in a few seconds. However, it seems probable that a situation which would lead to such a high corona current would instead trigger off a true lightning discharge. Little is known of the criteria which determine the transition from a corona into a complete spark, but probably a streamer carrying a current of several tenths of an ampere will develop immediately into a spark. As noted, such a spark would bypass the towline and relieve it of current.

2. Corona Line

Unfortunately the experimental basis for the curve ECJK of figure 19 is much less satisfactory and in the present state of our knowledge involves some very questionable extrapolation. The best basis for drawing the curve seems to be to use data observed in the laboratory with direct-current discharges across point-plane gaps and from fine wires. The data must then be extrapolated to higher voltages and to wider spacings than can be tried in the laboratory. Further complications arise (1) by reason of the rapid motion of the aircraft through the surrounding air, which may make the space charge conditions in flight radically different from those in the still air of the laboratory; and (2) because the complicated shape of the aircraft offers a rather indefinite plurality of corners from which corona may be emitted. Measurements of discharge current were therefore made with air blowing through the discharge gap, and other experiments with parts of airplanes and with, in one instance, a complete airplane charged to a high voltage. These experiments are described in sections V B 2a to V B 2d of this report. The curve ECDK in figure 19 (and also in fig. 33) is based on these experiments.

a. Point-plane corona currents.- The principal series of experiments to give a basis for estimating and extrapolating the value of corona current to greater effective spacing were made with the arrangement shown in figure 21. The "point" was a No. 0 sewing needle which protruded 2 centimeters from the surface of a 5-centimeter sphere. The needle was insulated from the shielding sphere and the microammeter indicated the current for the needle only. The sheet copper "plane" rested on the floor, which also contained a conducting grid of "hex-steel" reinforcement. Negative voltages up to 100,000 were applied to the point, and the resulting current was read by using the telescope, directed at the shielded microammeter. The results plotted to logarithmic scales for both coordinates are shown in lines A, B, C, and D near the bottom of figure 22. These lines were drawn with a slope of 2 and are seen to fit the observed points within the experimental error.

In an effort to obtain data at higher voltages the arrangement shown in figure 23 was used. The plane, now of limited area, was carried on an insulating support about 115 centimeters above the floor, and the center point of the rectifier was grounded. Data were obtained with both polarities. Typical results are shown in lines E, F, and G of figure 22. Additional measurements indicated that the discrepancy between curves A and F and between C and G (fig. 22) is the result of the limited size of the plane electrode, rather than of the different potential relative to ground. In figure 24 is plotted, for both polarities, the voltage required for a current of 100 microamperes. It is evident that in this range of fairly large currents polarity has little effect.

A third set of measurements at still higher voltages was made, using the floor as the plane while the shielded needle was maintained at a high negative potential by a 1.4-million-volt X-ray generator. This consisted of a cascade set of ten transformer-rectifier-capacitor units. The arrangement is shown in figure 25. The data obtained are plotted as lines H, I, and J in figure 22. Here again the lines have been drawn with a slope of 2. The lowest points fall somewhat off the line, partly because of the low precision in measuring the current and partly because the full corona has not developed. The graphs also show a curious flattening off at about 500 microamperes. It is thought probable that this flattening is the result of discharges from the surface of the 5-centimeter sphere or from neighboring parts of the shield at these very high voltages. The space charge from such a discharge would tend to shield the needle point itself. Lines K and L show data obtained with a longer point which extended 18 centimeters from the sphere. With this point there is no indication of flattening.

From the slope of the lines in figure 22 it seems evident that for a single isolated point at voltages well above that at which the discharge starts, the current varies as the square of the voltage (i.e., $I = kE^2$). To obtain a basis for extrapolating to greater spacings the coefficient k was derived from each of the observed curves, and in figure 26 k is plotted to a logarithmic scale as ordinate against the spacing, also logarithmically, as abscissa. It is seen that the dotted straight line AB which has a slope of unity fits the data except for the extreme points G and P. It seems possible that the presence of the walls and of other equipment, although at a distance of 10 meters from the discharge point, may have affected the conditions for the 8-meter spacing used for point P, and that for a true point-plane gap the line should continue straight bo B. However, points C and D which show the current from the 18-centimeter pointed electrode are each about the same distance (i.e., that corresponding to a factor of 1.37) above the corresponding points E and P, respectively, for the 2-centimeter needle, thus corroborating the location of P. It is therefore possible that data should be represented by the solid curve which extrapolates to F. In this graph a spacing of 30 meters, corresponding to the distance BD of figure 17, is indicated by the dashed line FB. The uncertainty introduced in choosing line GF or line AB for the extrapolation to 30 meters corresponds to a factor of 1.7 in the values of k and of current.

b. Current from aircraft.- A fourth series of experiments was made on completed aircraft structures - that is, ailerons and an entire airplane. In such a structure there are present great numbers of possible discharge points of various radii of curvature located in various relations to one another. It would be expected therefore that as the potential of such a structure was raised one point after another would begin to discharge so that the current would increase moro rapidly than in accordance with the simple square law of a single point. However, when a number of points closely adjacent are delivering current, their mutual interference makes the total current less than the sum of the currents which they would deliver separately.

These expectations were borne out by experiment. In figure 22 curve M shows the total current discharged from a Cessna aileron which was suspended with its trailing edge 36 centimeters above a conducting plane electrode. This control surface had a fabric covering stretched over a metal frame to which the high-voltage connection was made. As the voltage was raised the beads of glowing corona increased in number and in brightness, and the net rise in current is in proportion to the 5.7 power of the voltage. In a second experiment the plane electrode was shorter so that the corners of the aileron were less effective and curve N was obtained. The current is seen to be about one-half as great but to increase with voltage at a slightly greater rate. During these experiments the increase in the current with an increase in voltage was found to be roughly proportional to the number of new points seen to be discharging. These points could easily be counted in the darkened room.

For the final experiment a complete Fairchild PT-19-A airplane was suspended from an insulator string as shown in figure 27, and charged to a high negative potential by the X-ray generator. The clearance between the wing-tips and the walls was about 4.4 meters ($14\frac{1}{2}$ ft) and the tail was 5.5 meters (18 ft) from any grounded object. The plane of the wings was about 7 meters above the floor and 7 below the supporting crane beams. Figure 28 shows the general appearance of the corona discharge (St. Elmo's fire) when the potential was 1,200,000 volts. The camera was located about 30 feet above the airplane and to the left and rear. The spreading out of the spots of light is the result of a slight swinging of the craft by air currents during the course (10 min) of the photographic exposure. The wing tips are clearly outlined and the tail surfaces are seen foreshortened in the lower part of the photograph. The prominent discharge forward of the right wing comes from the pitot head. Two spots of light from the propeller tips and one at the propeller hub are visible. The other light spots are either corona beads on the support and connecting lead or are the result of some leakage of light from the vertical row of kenotron tubes (visible at the left) of the X-ray generator. This aircraft has a fuselage of fabric stretched over a steel tube skeleton while the wings are of plywood covered with aluminum paint. Apparently the paint provided enough conductivity to give about the same charge distribution as would be present with an all-metal airplane. The contrast between the discharge on the relative sharp trailing edge and the lack of it on the rounded leading edge of the wings was very marked.

The current is plotted in curve O of figure 22. The scale of ordinates for this curve is marked at the right. If the same scale were used as for the other curves, the points would be displaced one whole decade higher. A comparison of curve O with curve I (which is for a single point at 4 m spacing) indicates that at 600,000 volts the airplane would discharge 2.3 times as much current as a single unshielded point, while at 1,300,000 volts it would discharge 7.0 times as much as a single unshielded point.

The most likely value of corona current from an airplane at the high voltages and long distances occurring in flight can therefore be estimated by starting some point on curve O of figure 22, say x, as a base. This corresponds to 3 milliamperes at 1,000,000 volts and 4.4 meters. Then from the dash-line curve of figure 26 it is noted that in changing spacing from 4.4 meters to 30 meters k (i.e., the current at constant voltage) decreases by a factor of about 6.8, giving a current of 0.44 milliampere at 1,000,000 volts and 30 meters. Then the exponent 3.4 may be used to pass to other voltages. Thus at 3,000,000 volts and 30 meters the current from the aircraft would be

$$\frac{3}{6.8} \times \left(\frac{3,000,000}{1,000,000}\right)^{3.4} = 18.4 \text{ milliamperes}$$

or, more generally

$$I = 2.8 \times 10^{-11} \, (g_0 l)^{3.4} \qquad (2)$$

where I is in milliamperes and $(g_0 l)$ is in kilovolts.

Curve O of figure 22 shows no indication of becoming less steep at higher voltages, but the assumption that the exponent continues at the high value of 3.4 remains as a very serious source of uncertainty in the extrapolation. Another uncertainty has been introduced by the tacit assumption that the law of variation of current with spacing, shown in figure 26 to hold for isolated points, also holds for aircraft structures, although the law of variation of current with voltage is different in the two cases. The current computed from equation (2) constitutes the main contribution to the "corona line" ECDK of figures 19 and 33. These uncertainties are so large as probably to mask the variation of the current with the size of the aircraft. A reasonable assumption for this latter effect might be to consider corona current as proportional to the linear dimension of the craft.

c. Current from towlines.- In addition to the current which supplies the corona discharge from the extremities of the aircraft, there also may be a current which passes into the air directly from the surface of the towline itself. Although the primary electric gradient from cloud to cloud is taken as acting along the direction of the towline, the portions of line near its ends are at a potential which is very greatly different from that in the surrounding air a short distance away. Hence there is a very considerable radial component of electric gradient which may often be enough to cause partial breakdown of the air in the immediate neighborhood of the line.

This effect is clearly shown in figure 29. This is a photograph, taken in a darkened room, of the corona formed on a fine wire (No. 36 AWG) which was stretched between two brass balls, each 1.6 centimeters in diameter. The balls were supported by insulating paraffined threads so that each was about 12 centimeters away from a large metal plate, the plane of which was perpendicular to the axis of the wire. The right-hand plate was maintained at +70,000 volts and the other at -70,000 volts with respect to ground. There is a little corona from a spot on each of the spheres, that from the right-hand sphere being much the brighter. Most of the corona, however, comes from the wire because of the greater local gradient which results from its small radius of curvature. The characteristic difference between the beaded negative corona at the right and the uniform positive corona at the left is very marked. The short dark space at either end where the wire is shielded by the sphere and the stretch in the center where the radial gradient is less than that required to initiate corona are plainly evident.

To estimate the magnitude of these corona currents from the towline, it is necessary to use data obtained in laboratory measurements of the corona current from fine wires stretched along the axis of circular cylindrical outer electrodes; and to extrapolate these data to the case of higher voltages and larger-size wires and tubes.

To obtain a rough figure for the voltage which tends to produce the towline corona, it may be considered first that the only charges present are those on the clouds and the pair of charges $-Q$ and $+Q$ which are induced on the aircraft and which may be considered as if concentrated at their centers, each at a distance l from the center of the towline. The potential at any point x along the axis of the tow would, in this case, be given by

$$V = g_0 x - \frac{Q}{|l-x|} + \frac{Q}{|l+x|} \tag{3}$$

A distance a equal approximately to half the wing spread of the aircraft may be taken, and it may be assumed that (for the case in which the towline has zero resistance) Q will have such a value as to make $V = 0$ for points on some nearly spherical surface of radius a centered at $x = l$. Hence

$$0 = g_0(l - a) - \frac{Q}{a} + \frac{Q}{2l + a} \tag{4}$$

As previously noted, a is much less than l and, if terms in a/l are neglected, the magnitude of the induced charge is given by

$$Q = g_0 a l \tag{5}$$

Inserting this in equation (3) gives

$$V = g_0 \left\{ x - \frac{al}{|l-x|} + \frac{al}{|l+x|} \right\} \tag{6}$$

This function of x is plotted in terms of $g_0 l$ and x/l in figure 30.

It may be noted that the last term contributes only a small effect in the neighborhood of $x = + l$ and if this term is neglected, it can be shown that the point on the axis which has a potential $g_0 l$ is at $x = l + \sqrt{al}$. In the undisturbed field of the clouds this potential $(g_o l)$ occurs at $x = l$. The difference - namely, $\sqrt{al}$ - measures the distortion produced by the charge -Q and is the distance shown as DB in figure 17.

As shown in figure 30, the potential has a maximum at a distance d_m from the center of the aircraft. If the effect of the charge on the other aircraft is neglected, the value of d_m comes out as equal to $\sqrt{al}$, and the potential at this maximum is

$$V_m = g_o l \left(1 - 2\sqrt{\frac{a}{l}}\right) \text{ approximately} \qquad (7)$$

Thus far in this approximate treatment the electric charges distributed along the towline have been ignored. In the actual case, however, such induced charges will be present and will take on such a value and distribution as is required to bring the potential of each element of the towline to zero (or if the line has resistance, to the value corresponding to the resistance drop between that element and the center). The presence of these charges is the principal cause of the high radial component of electric gradient close to the towline, which produces the corona current which is to be estimated. The best basis for estimating the current therefrom seems to be to assume that the contribution of current from each element of length of the towline is the same as the corona current discharged from each element of length of a wire of the same size as the towline when it is placed at the axis of a cylinder of radius equal to $\sqrt{al}$ and maintained at a potential which differs from that of the cylinder by the amount given in equation (6). The principal uncertainty in this basis lies in the choice of the cylinder radius.

Unfortunately most of the data hitherto published on corona currents were obtained by using alternating voltage, and the observed values of current include capacitance effects. Also, electrical engineers usually have been interested only in cases in which the applied voltages exceeded the critical value at which corona starts by only a small margin, while in the present problem the voltage on parts of the line may be many times this critical value. The classic work by Watson (reference 12) using direct current covers voltages only slightly above critical. The experiments of Farwell (reference 13) cover a good range of voltage but include only one diameter (4.45 cm) of outer tube. In view of this situation, further experiments were undertaken using larger tube diametors - namely, 50 centimeters and 100 centimeters - and higher voltages. The apparatus was arranged as shown in figure 31. To avoid the loss of time which would have been required for constructing an elaborate outer cylinder with the conventional guard sections at either end, the end effects were minimized by enclosing the upper end of the wire in a cylindrical shield and attaching a 9-centimeter sphere to the lower end. The residual end effects were then eliminated by taking a second reading with a different length l_2 of wire between the guard and the sphere, as indicated by the dotted lines. Even with the longer wire the sphere was well above the bottom of the outer cylinder, and it has been assumed that the increase in current between the two conditions is the current corresponding to the increase in length.

Figure 32 shows the results of these measurements and also some of Farwell's data. Here the current per unit length (μa per cm) is plotted as ordinate against the voltage between wire and cylinder (in kv) as abscissa, both to logarithmic scales. The wire was negative in these experiments, but for one combination of wire and cylinder diameters, additional measurements with the wire positive indicated substantially the same value of current, except at very low voltages.

An approximate theoretical treatment of the effect of the space charge around the wire in limiting the corona current (see appendix A) indicates that the voltage E should be related to the current i per unit length and the outer radius c by an equation of the form

$$E = c\sqrt{\frac{2i}{u}} + B \tag{8}$$

where B is a function of the current and of the radius of the wire b but not of c. In column 5 of table 2 are shown the values of the quantity $\sqrt{\frac{2}{u}}$ derived by takin. pairs of values of E and c for various values of i and b. It is seen that this quantity is nearly independent of i and of b and has a value corresponding to a mobility u = 1.36 centimeters per second for one volt per centimeter. This is in satisfactory agreement with the usually quoted value 1.8. By using the mean value 1.15 for $\sqrt{\frac{2}{u}}$ in equation (8) the values of B given in column 6 of table 2 have been computed. These values are small relative to the total voltage given in column 4, except for the case of Farwell's small cylinder. They show a definite minimum at a current of about 5 microamperes per centimeter, but the change in B with current does not seem to be very great and will be neglected in the present rough extrapolation. The variation of B with wire diameter is quite marked, as might be expected. When B is plotted against the logarithm of the wire diameter b the result is approximately a straight line which, if extended to a radius of 1.05 centimeters (diam. = 13/16 in.), gives a mean value for B of 80 kilovolts. This will be used in computing corona currents for towlines of this diameter. By taking, rather arbitrarily, the value 30 meters for c, equation (8) becomes

$$E = 3450 \sqrt{i} + 80 \tag{9}$$

where E is in kilovolts and i is in milliamperes per centimeter.

If this relation is combined with equation (6), values of current can be calculated for successive sections of the towline and the summation of their increments gives the total current. For the values given this comes out at 0.5, 1.5, and 6.3 milliamperes for $g_o l$ equal to 3000, 5000, and 10,000 kilovolts, respectively. These values turn out to be almost negligible in comparison with the corona current from the airplane as given by equation (2). However, the computed value for the corona current from the towline will vary almost inversely as the square of the equivalent radius c, and if this had been chosen as 11 meters instead of 30 meters, the towline corona current at $g_o l$ = 5000 kilovolts would have been as large as that from the airplane. This indefiniteness in the equivalent radius therefore remains as one of the worst of the many sources of uncertainty in these estimates.

d. Air velocity tests.- In the foregoing discussion the effect of the relative motion of the aircraft and the air in which the corona discharge is occurring has been neglected. Theoretical considerations would indicate that of the value of current of concern here, the space charge accumulating in the neighborhood of the discharge point would materially affect the potential gradient. This effect would be expected to amount to a very considerable part of the total applied voltage as the spacing from point to plane becomes larger. If the velocity of the air relative to the electrodes is fast relative to the drift velocity of the ions through the air, it would be expected that this space charge would be swept away. Hence at first sight it would appear that the current in flight for a given voltage might be materially greater than that observed at the same voltage in "still air."

To test this hypothesis, experiments were made with the point-plane gap shown in figures 21 and 23 by blowing a jet of air from a 1-horsepower blower into the gap. Trials were made with the jet (a) transverse to the axis of the gap, (b) along the axis and directed toward the needle point, and (c) along the axis and directed toward the plane. In this third arrangement the charged needle was supported in the center of the (insulating) air nozzle. The velocity of the air immediately in front of the nozzle was 7000 centimeters per second, and at a distance of 10 centimeters the jet had expanded to a diameter of about 3 centimeters and had a velocity of about 3000 centimeters per second.

It was found that with either polarity the presence of the air jet seemed to interfere with the formation of long streamers so that the voltage could be raised to a higher value before sparkover occurred. Also since the presence of a streamer usually corresponds to an increased current, the starting of the blower actually reduced the current somewhat at the higher voltages. At the lower voltages where no prominent streamers were present anyway, the starting of the blower caused a definite but small increase in current. This increase, however, was seldom more than 3 or 4 percent.

At first it was thought that the observed effect was small because the electrode spacing was small and much of the total difference of potential might be concentrated very near the point where the ion velocity is high. Accordingly an airplane propeller was attached to an electric motor and placed so as to blow air between the discharge point and the grounded floor plane in the experiments at spacings of 2, 4, and 8 meters. The propeller was run at about 680 rpm and produced an air velocity of about 800 centimeters per second (19 mph) over most of the discharge gap. This velocity is, of course, small compared to glider speeds but is large compared to the drift velocity of ions in a field less than 400 volts per centimeter. At the largest spacings quite a fraction of the entire space between the electrodes is subjected to a gradient of less than this value. However, in the experiments this air velocity was found to have practically no effect on the discharge current. In fact, at the highest voltage there was a slight (4 percent) decrease in current when the propeller was started. This is shown by the position of the points marked P in figure 22 relative to those marked R for which the propeller was not running.

Although these experiments cannot be taken as conclusive, because of the lower air velocities and the shorter effective spacing of the electrodes as compared with flight conditions, it would appear that in the absence of any better evidence the effects of air velocity on corona current should be neglected.

C. PREVENTIVE MEASURES AGAINST CORONA CURRENTS

1. General Relations

From the diagram (fig. 19), it is obvious that there are two possible procedures by which the problem may be attacked. The first procedure is to maintain the towline at such a high resistance that the current is limited to a low value and cannot cause much heating or other damage. The second procedure is to keep the resistance of the towline at such a low value that the heating is negligible even though the current may be large.

The quantitative distinction between "high" and "low" resistance can be best seen if there is added to the current-voltage diagram of figure 19 a family of curves, such as I and II of figure 33, which corresponds to fixed values of total heat development in the line. These curves of constant power are rectangular hyperbolas with AO and AB as asymptotes. In figure 33 curve I corresponds to 10 kilowatts and curve II to 100 kilowatts in the half-length of towline for which the diagram is constructed. If the total line is 200 meters (600 ft) long, these curves correspond to average heat productions of 1 watt per centimeter and 10 watts per centimeter, respectively. If the resistance of the towline had an intermediate value such as 2500 ohms per centimeter, corresponding to the line AH, the intersection of AH with ECK comes at C and corresponds to the dangerous heating of nearly 10 watts per centimeter. However, if the towline has a resistance of 50 ohms per centimeter, corresponding to the steeper line AL, the intersection L falls near the 1-watt-per-centimeter curve and the hazard is much less. Similarly if the resistance of the towline is 100,000 ohms per centimeter and its line falls at AM intersecting ECK at M, the heat development is again found to be low. Hence it may be concluded that resistances greater than 100,000 ohms per centimeter are high and those less than 50 ohms per centimeter are low. It is evident that a line may be low in resistance in this sense even when it has a resistance 10,000 times that of any metal cable.

In table 1 are given typical values of resistance measured on lines of various materials, under different conditions. It appears that while most textile ropes when clean and dry are in the high class, they all come into the intermediate dangerous class when wet.

It also follows from the diagram that far less severe storm conditions (i.e., with the line A'B' and its family of constant power curves further to the left) the dangerous intermediate range of cable resistance is narrow. Thus, for a cloud gradient of 375 volts per centimeter as indicated by the storm line A'B', the upper limit for a safe low resistance rope, as indicated by the line L'A' through the intersection of the 1-watt locus I' with ECK, is about 1800 ohms per centimeter; while the lower limit for a safe high-resistance rope, as shown by M'A', is 15,000 ohms per centimeter.

2. Use of High-Resistance Cable

Considering now the first remedial procedure, that of keeping the resistance of the towline high, it may be seen that the primary difficulty arises from the moisture which is likely to be taken up by the towline whenever it is flown through a cloud. At first sight it would seem as though the heating produced when the damp towline entered the electric field would serve to dry it out and restore the high resistance. Laboratory experiments indicate, however, that this drying is never uniform. A portion which is initially drier and of higher resistance than the rest will be heated by the current more than adjacent portions and will soon have a considerable part of the total voltage across it. This locally increased voltage gradient causes arcing across the driest sections. These arcs, as shown in figure 16, also burn and char the textile (and melt it if it is nylon) and weaken it rapidly.

It is evident from these considerations that the insertion of one (or more) sections of rigid high-grade insulating material is useless because a goodly fraction of the entire voltage will promptly accumulate across them and produce a flashover.

If the entire length can be kept at such a high resistance that the current is limited to a few microamperes, a lack of uniformity is not so serious because a slight corona discharge can bypass the portions of highest resistance without producing further concentrations of gradient or serious heating.

The following experiments were tried in an effort to solve the problem along this line. Samples of nylon rope were treated by dipping them (1) in transformer oil (a refined mineral oil of about 58 Saybolt viscosity); (2) in liquid Saran plastic; and (3) in an 11-percent solution of polyvinyl isobutyl ether. A fourth sample was treated by the General Electric Company with their "Drifilm" process.

After drying, each sample was fastened vertically between an insulator which hung on the hook of a chain hoist and a platform which could be loaded with weights. A pair of electrodes were attached a measured distance (in this case 10 cm) apart. Each electrode consisted of a copper tube which fitted snugly over the rope for about 6 inches but which was flared out at the inner end and joined to a flat disk about 6 inches in diameter. The outer edge of this disk was bent back and rounded. These electrodes, which are shown in figure 34, served to expose the sample between them to a fairly uniform electric field and to minimize the tendency for the field to be concentrated at the ends of the specimen and to cause local sparking there.

While the samples were dry, their resistance was so high that the voltage applied to the electrodes could be raised, without causing an appreciable current, almost to the value at which a spark would jump through the air. The samples were then subjected to a very finely divided spray of distilled water from a paint spray gun which delivered about 0.056 gram of water per square centimeter of exposure surface per minute. This treatment should be analogous to flying at 120 miles per hour with an angle of 6° between the rope and the direction of flight in a cloud having 1.7 grams of water per cubic meter.

Under this treatment the rope which had been dipped in transformer oil (5/8-in. rope, loaded with 400 lb tension) decreased in resistance in 10 seconds to about 0.3 megohm per centimeter allowing a current of 2 milliamperes to flow. The current was held at this value. After about 30 seconds, sparks and a red glow were noted at certain spots, and $1\frac{3}{4}$ minutes after the current was applied one strand broke and the test was stopped.

The Saran-treated sample (1/4-in. rope loaded with 62 lb tension) was sprayed for 1 minute. Voltage was then applied and raised until the current was 1 milliampere (resistance then 3.3 megohms per cm). After 40 seconds the rope began to burn. On the basis of relative cross section this behavior is equivalent to failure at 6 milliamperes for a 5/8-inch rope.

The sample treated with polyvinyl isobutyl ether (1/4-in. rope loaded with 62 lb tension) was sprayed for 30 seconds and dropped in resistance to 2.4 megohms per centimeter. After a current of 1 milliampere had been flowing for only 12 seconds, one strand broke and another was partially melted.

The 5/8-inch nylon rope which had been treated by the GE Dri-film process was sprayed for 30 seconds with distilled water and then could carry 1 milliampere at 27,000 volts (on the 10-cm sample). The resistance gradually rose, and after 10 minutes at this current the sample showed traces of slight burning all along its length. It was again sprayed for 20 seconds, and a current of 5 milliamperes was applied. In 30 seconds a red glow appeared in spots, and after $1\frac{3}{4}$ minutes at 5 milliamperes one strand burned in two and the others were found to be badly charred. Figure 34 is a photograph of this specimen after the test.

These unsuccessful results seem to indicate that the capillary action holds enough water between the nylon fibers to give too much conductivity even after these water-repellant treatments. In an earlier experiment a piece of rubber tubing about 1 centimeter in diameter and several feet long was dipped in tap water and then subjected to a high alternating voltage. As the water dried from the surface, temporary arcs were produced which bridged across the dry portions, but after about 30 seconds the drying had proceeded to such an extent that the current was completely interrupted. The tubing showed very little damage as a result of this operation. This suggests that about the only possibility of making the nylon rope permanently insulating is to devise some means of encasing it for its entire length in a thin-walled elastic tube. Such a coating would also give a rope that would float and thus be desirable for marine work.

3. Use of Low-Resistance Cable

A number of experiments were made to develop the second remedial procedure of making the rope a sufficiently good conductor to carry the corona current without damage.

a. Metal core.- The most obvious procedure is to provide a small metallic conductor in parallel with the textile rope. Because of the great elongation under load of nylon, means must be arranged to avoid the breaking of the metal when the rope stretches. Loose loops in the wire are objectionable because of snarling. If the wire is wrapped in a helix outside the rope, it tends to constrict and develop excessive tension unless it is very loose when unstressed. A wire helix of small diameter laid along the axis of the rope avoids all of these mechanical troubles and can easily carry the corona current. However, in case of a direct lightning stroke to the aircraft, such as is discussed in section III, the wire would be volatilized and the high-current arc would be initiated inside the rope.

To try out this arrangement, a sample was made up with a helix of No. 30 AWG steel wire in the center. When the 22,000-ampere surge current passed through it, the hot gases which blew out through the interstices caused considerable melting of the rope, as shown in figure 35. Here the strands have been separated to show the scorching.

b. Conducting solutions.- It was at first hoped that flight through clouds might wet the rope enough to insure sufficient conductivity. To test this point a number of rope samples were soaked in distilled water to make them conducting. In these tests moistened cotton was wedged into the chink between the electrode and the rope to insure good contact. After 2 or 3 minutes soaking, the samples had absorbed all the water they would hold, which is about 30 percent of their dry weight. When tension was applied to the sample (about 0.1 of their ultimate breaking strength), approximately one-third of this water was squeezed out. When current was applied to these samples, they dried out nonuniformly, and a spark would then jump across whatever small section first dried out to a high resistance. After sparking started it was only a few seconds for the small-size rope, and not over 30 seconds for the larger sizes, until the sample was weakened enough by the burning to drop its load. In order to save as many of the rope samples as possible for further tests the current was taken off just as the sparking started. The curves in figure 38* show the time required to reach this critical, or sparking, point as a function of the current through the sample for three different sizes of rope. In some of the tests the current was kept on until the sample had failed - that is, until its load was dropped. Figures 36 and 37 show a sample of 13/16-inch-diameter nylon rope after a current of 30 milliamperes had flowed through it for 1 minute and 50 seconds.

In view of these rather disconcerting results other methods for making the nylon towrope more definitely conducting were investigated. When solutions of either (1) 4-percent sodium chloride or (2) 4-percent calcium chloride were used in place of the distilled water, the rope was found to be sufficiently conducting to carry currents up to 30 milliamperes (for the 5/8-in. diam. rope) for 25 minutes with no signs of distress. However, in a thunderstorm the salt solution might be highly diluted by rain water in a short time. Tests made on a sample first soaked in a 4-percent solution of calcium chloride, dried, and then repeatedly dipped in distilled water and dried, indicated that after about 15 dippings the decrease in resistance resulting from the calcium chloride had disappeared.

c. <u>Permanent impregnation</u>.- A more desirable method of treatment for the rope would be to impregnate it with some material which would make it a permanent conductor even after repeated wetting and drying. Some samples were made by dipping the rope in "ethocel lacquer" obtained from the Dow Chemical Company, using several different concentrations. Samples which were found to be sufficiently conducting had enough "ethocel" between their fibers to make them quite stiff and after some handling this material would crack and particles would fall off, thus leaving "spots" of high resistance. This condition caused sparking and burning of the rope when voltage was applied.

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*Fig. 38 is on the same page with fig. 33.

Another treatment is to dip the sample in aquadag (colloidal graphite in water). Concentrations from 1 part aquadag and 3 parts distilled water to 1 part aquadag and 20 parts distilled water were tried on three sizes of nylon rope (1/4, 5/8, and 13/16 in. diam.). The resistance of the sample decreased sharply (with some irregularity) as the concentration of aquadag in the solution was increased. Low resistances (down to 500 ohms per cm) were easily obtained, and the flexibility of the rope was not noticeably affected. Mechanical stress such as repeated application and removal of tension, and also repeated soaking in water, did not noticeably increase the resistance of the sample. Even vigorous scrubbing with soap and water only increased the resistance of a sample from 0.31 megohm to 1.5 megohms.

A number of specimens were treated with aquadag and then subjected to an electrical test while under tension. In these tests tinfoil was wedged into the flared portion of the electrode to insure good electrical contact to the rope, and the applied direct-current voltage was adjusted as necessary to hold the current at a predetermined value. After 10 minutes at one value of current the voltage was removed and the specimen was allowed to cool nearly to room temperature. This procedure was then repeated with a higher value of current and a correspondingly greater heating of the sample. In these trials the specimen heated up fairly uniformly throughout its length and there was no sign of local arcing such as develops from the drying out of wet ropes. The 10-minute interval was long enough for conditions nearly to reach equilibrium. Finally, a value of current was reached at which the rope showed signs of distress, the current became unsteady, smoke was sometimes noted, and one or more strands broke before the 10 minutes had elapsed. The results are shown in table 3. Here the current at the time of failure is shown in column 9. Column 10 gives the power developed as heat per centimeter length of rope, while column 11 gives the quotient obtained by dividing this value by the exposed surface area of the rope. The fact that this latter figure decreases systematically as the diameter of the rope increases indicates that there is probably a considerable difference in temperature between the center and the surface of the rope. A thick rope is therefore less effectively cooled and dissipates less heat per unit area from its surface when it is at the same average internal temperature as a thinner rope.

In flight the relative motion of the air past the rope will give a marked cooling effect. To simulate this condition, specimen 12 (which was substantially similar to 11a) was tested in an air stream. An insulating tube about 1 inch in internal diameter surrounded the 1/4-inch-diameter specimen, and a blower forced air at a velocity of about 200 feet per second (135 mph) through the space between rope and tube. It will be noted from table 3 that the power dissipation at failure was about doubled by the cooling action of this air blast. However, in the case of a large rope the gain probably will be by a rather smaller factor, because of the greater temperature drop between the center and the outer layers.

The value of resistance given in column 4 is that measured by a "megohm bridge" with about 100 volts applied to the 10-centimeter specimen. The value given in column 5 is computed from the voltage observed while the specimen was carrying a current nearly at its limit. The difference in these values is the result of three effects. When tension is applied to the rope it decreases slightly in cross section, but the particles of graphite are brought into better contact and the electrical resistance decreases. At the higher voltages a "coherer action" seems to occur and bridges develop between particles and cause a further decrease in resistance. Also as the temperature rises, even at constant voltage, the resistance decreases somewhat. (This observation is contrary to the usually quoted positive temperature coefficient of resistivity of graphite in bulk, but is in agreement with the negative coefficient of carbon.)

Most of the trials listed in table 3 were made with specimens of fairly high resistance, in order that destructive effects could be obtained with currents within the range of the available direct-current source. Specimen "B", however, of 13/16-inch rope, was treated with three dips of one-third dilution aquadag to which approximately 0.1 percent of aerosol had been added and had a resistance after drying at room temperature of only 500 ohms per centimeter. It was tested under mechanical load as previously described, except that alternating current was used instead of direct and each value of current was held for 15 minutes. Immediately after each run a mercury thermometer was placed against the outer surface of the rope and surrounded by a thick pad of cotton. The temperatures indicated by the thermometer were found to increase linearly with the watts per unit length at the rate of 37° C per watt per centimeter. For a current of 200 milliamperes, the thermometer indicated 85° C, and the rope held a load of 3500 pounds without failure. Early in the test, at 60 milliamperes, local heating developed under one electrode because of poor contact. The load was removed and tinfoil packed in place to give a more effective contact. The load, which had been 4000 pounds, was thereafter kept at 3500 pounds. Shortly after the current was raised to 240 milliamperes the sample began to smoke and melt at both contacts. The mechanical load was removed and the specimen then appeared as in figure 39. It will be noted that the lay has increased in the section between the electrodes and that there is some loss in area under the electrodes. The melting, shown in detail in figure 40, at one end, however, was worse than in most of the arc-over trials shown in section III, although the rope was still able to hold 3500 pounds. During the course of the experiments the resistance of the specimen showed a permanent decrease, as if the particles of graphite were being gradually squeezed into better contact. At the end of the test, under load and hot, the resistance was only about 40 ohms per centimeter, although it was initially 500 ohms per centimeter when cold.

The specific heat of nylon, approximately 2.3 joules per gram-degree, is so large that the storage of heat during the relatively short time that the towline is likely to be exposed to the most intense part of the thunderstorm field may play an important and helpful role. Thus, if a temperature rise of 100° C were required to weaken the rope to a dangerous extent, a peak of 5 watts per centimeter could be absorbed provided it lasted only 45 seconds.

D. QUALITATIVE MODEL EXPERIMENT

As a laboratory "stunt," to obtain a qualitative representation of the phenomena discussed in this report, the experiment shown in figure 41 was set up. Two tiny metal models (wing span 2 in.) were connected by a No. 36 (0.005-in. diam.) copper wire and supported between two large metal plates which represented the clouds. The right- and left-hand plates were charged to +70,000 and to -70,000 volts, respectively, with respect to ground. The resulting corona discharge from the models and from the wire is shown in figure 41, and the difference in character of the concentrated, intense negative beads and the more diffuse and extended positive glow is very evident. In spite of the marked difference in the illumination produced at the two ends, the currents must, of course, be equal. The dark section of the towline is nearly centered and, this fact shows that the balance of current was attained with the models and wire at a potential only slightly positive with respect to ground. In such a model experiment it cannot be hoped to duplicate many of the essential features of the phenomenon, such as the radii of curvature of points and edges and the distance from aircraft to "clouds," and thus the experiment has no quantitative value.

On the other hand, many qualitative features are plainly visible, such as the location of the discharge on the salient points of the aircraft, the existence of a maximum of radial potential gradient a short distance farther along the cable, and the neutral zone of low radial gradient near the center of the towline.

VI. CONCLUSIONS

The foregoing discussion of the possible electrical effects on glider towlines in a thunderstorm leads to a number of rather definite conclusions.

Metal Towlines

(1) From the purely electrical point of view a metal towline is to be preferred. If of the minimum weight needed to give the required tensile strength, it would be immune to damage from corona currents and from a lightning stroke to the aircraft at its ends.

(2) If it is desired to guard against the rather remote chance of a direct lightning stroke to the towline itself, the metal line can be adequately protected by covering it with a thin layer of insulation outside of which is a metal braid. This type of construction also would provide a two-conductor connection for communication between the aircraft.

Textile Towlines

(1) If nonelectrical considerations dictate the use of a textile rope such as nylon, measures should be taken to minimize its electrical hazards. Untreated textile rope is liable to be seriously overheated and burned (or melted) if the tow operates for even a few minutes in the intense electric field which is

present within a few miles of any thunderstorm. The current-voltage diagram shown in figures 19 and 33 of this report offers a useful, though approximate, means for estimating the magnitude of these dangerous towline currents for any assumed combination of storm intensity, towline resistance and corona discharge characteristics of the aircraft. To estimate these characteristics some very extreme and questionable extrapolations must be made, but even on the most optimistic basis that is at all reasonable there appears to be a very real hazard.

(2) Of those methods tried, the use of a treatment, such as dipping in aquadag, which will make the rope permanently conducting, offers the most promising remedy. This procedure has been found to give a conductance which enables the towline to carry, without serious damage, the currents set up when operating in all but the most intensely stressed portions of the thundercloud.

(3) If a treatment could be developed which would coat the outer surface of the rope with a thin, smooth, elastic, waterproof skin, this treatment would also remove the hazard.

(4) A textile towrope, even when rendered conducting, probably will flash over and be undamaged by a direct lightning stroke either to the aircraft or to the rope itself, particularly if arcing rings are provided at the ends.

VII. APPENDIX A

SPACE CHARGE EFFECTS IN A CYLINDRICAL FIELD

In view of the necessity for extrapolating laboratory data on the corona current from a wire in a coaxial cylinder to large values of voltage and radius, it was thought worth while to develop the following theoretical relationships as a guide to such an extrapolation. A somewhat similar treatment has been attempted by Fazel and Parsons. (See reference 14.) However, they introduce unnecessarily the tacit assumption that the space charge density is independent of the radius and this assumption affects, and in our opinion, vitiates, their result.

Consider a wire of radius b stretched along the axis of a circular cylinder of radius c and maintained at a constant voltage E with respect to the cylinder. This voltage is assumed to be well above that at which corona begins. In the immediate neighborhood of the wire, out to a radius r_0, a very complex process involving ionization, recombination and the emission of radiation is taking place. Outside of r_c, however, the electric gradient is assumed to be less than the critical value g_0, at which ionization by collision by electrons occurs to an appreciable extent, and the only process which goes on is the drift of ions, of the same sign as that of the charge on the wire, toward the outer cylinder under the action of the electric gradient. This gradient g, as well as the volume density of space charge q and the velocity v of the ions relative to the air, which is assumed to be stationary, is, in general, a function of radius r. The mobility of the ions u is, however, assumed to be constant.

In the steady state there can be no progressive accumulation of charge anywhere in the circuit and the total current i per unit length across any cylindrical surface of radius r coaxial with the wire must be the same as that across any other such surface. That is the current i which is given by

$$i = 2\pi rqv \tag{A1}$$

must itself be independent of r.

By the definition of mobility, the velocity v is given by

$$v = gu \tag{A2}$$

Combining (A2) and (A1) gives

$$q = \frac{i}{2\pi urg} \tag{A3}$$

Now in the space between $r = r_c$ and $r = c$ the potential V must satisfy Poisson's equation

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dV}{dr}\right) = -4\pi q \tag{A4}$$

By introducing

$$g = -\frac{dV}{dr} \qquad \text{(A5)}$$

and q from equation (A3) into equation (A4) gives

$$\frac{1}{r}\frac{d}{dr}(rg) = +\frac{2i}{urg} \qquad \text{(A6)}$$

or

$$r\frac{dg}{dr} + g - \frac{2i}{ug} = 0 \qquad \text{(A7)}$$

To integrate this,

$$z = g^2,\ dz = 2g\ dg \qquad \text{(A8)}$$

may be substituted and then the variables separated to get

$$\frac{udz}{(2i - uz)} = \frac{2dr}{r} \qquad \text{(A9)}$$

whence

$$z = \frac{2i}{u} - \frac{C}{r^2} \qquad \text{(A10)}$$

or by equation (A8)

$$g = \sqrt{\frac{2i}{u} - \frac{C}{r^2}} \qquad \text{(A11)}$$

where C is a constant of integration. To evaluate C it may be noted that a reasonable value for the mobility u is 1.5 centimeters per second for one volt per centimeter (450 esu), and a fairly high value of current is 10 microamperes per centimeter (3×10^4 esu). For these values the first term in the right-hand member of equation (A10) is only 130, yet at radii near the value r_c the gradient g must be near g_c or 100 esu. Hence z must be nearly 10^4 esu and must be nearly equal to the last term of equation (A10). Hence

$$C = -g_c^2 r_c^2 \text{ approximately} \tag{A12}$$

To deduce the total voltage between wire and cylinder, g should be integrated with respect to r from b to c. However, the radical in equation (A11) makes this process difficult mathematically. To obtain an approximation, it is noted that there is some intermediate radius r_m for which the two terms under the radical sign are equal. This value of r is

$$r_m = g_c r_c \sqrt{\frac{u}{2i}} \tag{A13}$$

For values of r much less than this the second term preponderates; hence

$$g = \frac{g_c r_c}{r} \tag{A14}$$

while for values of r much larger than r_m it may be written

$$g = \sqrt{\frac{2i}{u}} \tag{A15}$$

For values of r nearly equal to r_m the true value of g will be greater than that given by either (A14) or (A15), but the excess will not be greater than by a factor of $\sqrt{2}$. A fair approximation to the voltage between wire and cylinder is therefore obtained by adding to E_c the voltage across the corona proper between $r = b$ and $r = r_c$, the contribution obtained by integrating (A14) from $r = r_c$ to $r = r_m$ and the contribution obtained by integrating (A15) from $r = r_m$ to $r = c$. This yields

$$E = E_c + g_c r_c \log_e \frac{r_m}{r_c} + \sqrt{\frac{2i}{u}}\,(c - r_m) \tag{A16}$$

on inserting the value of r_m from equation (A13) and rearranging this becomes

$$E = c\sqrt{\frac{2i}{u}} + g_c r_c \left\{\log_e\left(g_c\sqrt{\frac{u}{2i}}\right) - 1\right\} + E_o \tag{A17}$$

This is in the form

$$E = c\sqrt{\frac{2i}{u}} + B \tag{A18}$$

where the quantity B is a function of i and of the wire radius b but is not dependent on the cylinder radius c.

By combining data for the same current and wire radius but for two different cylinder radii B can be eliminated and an experimental value found for u. Thus

$$\frac{1}{\sqrt{i}} \times \frac{(E_1 - E_2)}{(c_1 - c_2)} = \sqrt{\frac{2}{u}} \tag{A19}$$

and values of this quantity are listed in column 5 of table 2. The constancy of these values over a wide range of E and c and the agreement of the experimental value for u - namely, 1.4 centimeters per second for one volt per centimeter with the value 1.8 usually given for negative molecular ions - is quite satisfactory and tends to indicate that equation (A18) should be a safe guide for the extrapolations. By inserting the mean value thus found in equation (A18) empirical values of B can be found. These are listed in column 6.

National Bureau of Standards,
Washington, D. C., December 17, 1943.

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TABLE 1.- RESISTANCE OF ROPE IN OHMS PER CENTIMETER OF LENGTH

Sample number	Type of rope	In air			After 5 min in tap water		After 40 hr in tap water		After 40 hr in sea water		
		RH 20% T 20°C	RH 45% T 25°C	RH 95% T 35°C	Wet	Surface wiped	Wet	Surface wiped	Surface wiped	Dried 80 hr in air RH 30% T 25°C	48 hr in air RH 95% T 25°C
1	1/2" jute, A	2×10^{10}	6×10^{8}	3×10^{6}	1×10^{4}	2×10^{5}	6×10^{3}	1×10^{4}	3×10^{2}	2×10^{8}	2×10^{3}
2	3/4" jute, A	9×10^{9}	2×10^{9}	2×10^{6}	1×10^{4}	2×10^{5}	9×10^{3}	2×10^{4}	3×10^{2}	1×10^{8}	9×10^{3}
3	1/2" sisal	2×10^{10}	2×10^{8}	2×10^{6}	2×10^{4}	3×10^{4}	3×10^{3}	3×10^{3}	3×10^{2}	9×10^{8}	9×10^{3}
4	3/4" sisal	9×10^{9}	6×10^{7}	9×10^{5}	9×10^{3}	2×10^{4}	2×10^{3}	2×10^{3}	2×10^{8}	3×10^{8}	6×10^{3}
5	1/2" jute, B	$>6 \times 10^{10}$	2×10^{9}	1×10^{7}	3×10^{4}	6×10^{5}	2×10^{4}	3×10^{4}	3×10^{2}	6×10^{9}	2×10^{4}
6	3/4" jute, B	6×10^{10}	6×10^{8}	6×10^{6}	3×10^{4}	1×10^{6}	1×10^{4}	3×10^{4}	3×10^{2}	9×10^{8}	6×10^{3}
7	3/4" manila	2×10^{9}	9×10^{6}	2×10^{5}	9×10^{3}	1×10^{4}	9×10^{2}	1×10^{3}	2×10^{2}	3×10^{8}	6×10^{3}
8	1/2" cotton	1×10^{10}	2×10^{8}	6×10^{5}	2×10^{4}	6×10^{5}	3×10^{3}	3×10^{3}	3×10^{2}	3×10^{8}	6×10^{3}
9	3/4" cotton	3×10^{9}	3×10^{7}	2×10^{5}	2×10^{4}	1×10^{5}	9×10^{2}	9×10^{2}	2×10^{2}	3×10^{8}	6×10^{3}
10	13/16" nylon	$>6 \times 10^{10}$	$>6 \times 10^{10}$	*9×10^{8}	*2×10^{4}	3×10^{4}			2×10^{2}	$>6 \times 10^{10}$	2×10^{3}

*After 5 min in distilled water.

TABLE 2

1	2	3	4	5	6	7
Wire radius, b (cm)	Current per cm, i (μa)	Tube radius, c (cm)	Voltage, E (kv)	$\frac{\Delta E}{\Delta C\sqrt{i}} = \sqrt{\frac{2}{u}}$	B (kv)	Average b (kv)
0.026	10	50	193			
		25	100	1.18	7.6	
		2.22*	12.3	1.22	3.7	
	5	50	136			
		25	71	1.16	6.0	
		2.2	11	1.18	5.1	
	2	50	86			
		25	46.2	1.13	6.4	
		2.22*	10	1.13	6.5	
	1	50	63			
		25	35	1.12	7.0	
		2.22*	9.8	1.11	7.3	6.2
.051	10	50	207			
		25	112	1.20	17	
	5	50	148			
		25	80.5	1.20	13	
	2	50	95			
		25	57	1.08	19	
	1	50	71			
		25	45.2	1.03	19	17
.32	10	50	250		60	
	5	50	176		41	
	2	50	133		57	
	1	50	118		66	56
				Average 1.15		

Whence $u = 410$ esu $\Leftrightarrow$ 1.36 cm^2/volt-sec

*Data for c = 2.22 cm from Farwell (reference 13)

TABLE 3.- NYLON ROPES TREATED WITH AQUADAG

Specimen number	Diameter (in.)	Treatment	Resistance (ohm/cm)		Test load (lb)	Withstood for 10 min		Failed at			
			Cold	Under load		Current (ma)	power (w/cm)	Current (ma)	Power (w/cm)	Power (w/sq cm)	Time (min.)
1	2	3	4	5	6	7	8	9	10	11	12
11a	1/4	1 dip; 1/3 dilution then stressed, washed soap and water, prolonged soaking and drying	80,000	35,000	400	5.2	0.9	6	1.5	0.7	1.5
12	1/4	Same as 11a, tested in air stream 200 ft/sec	100,000	20,000	400	10	2.3	12	3	1.5	5.5
6	1/4	1 dip; 1/7 dilution	200,000	50,000	212	3.1	.5	5	1.2	.6	1.8
8	5/8	2 dips; 1/14 dilution plus 1 dip; 1/20 dilution	40,000	20,000	2400	8	1.3	9	1.8	.4	8.5
4	13/16	2 dips; 1/10 dilution	900,000	100,000	3950	3	1.0	4	1.9	.3	7.5
B	13/16	1 dip; 1/3 dilution	500	40	3500	220	1.97	240	5.3	.8	1

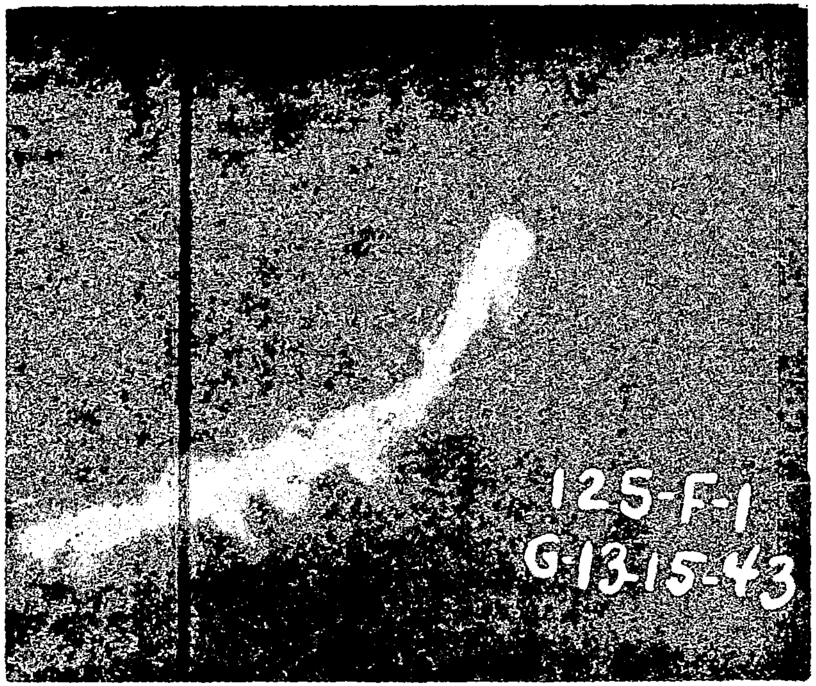


Figure 1.- A transient discharge striking and following along a wet, 1/4-inch cotten sash cord, 2 feet long. Crest current 25,000 amperes, duration about 40 microseconds. The cord showed no damage after the stroke.

Figure 2.- Sixty-cycle, 4-ampere arc rising along a dry, untreated nylon rope, 13/16-inch diam. Exposure of 0.01 second shows illumination during parts of two half-cycles.

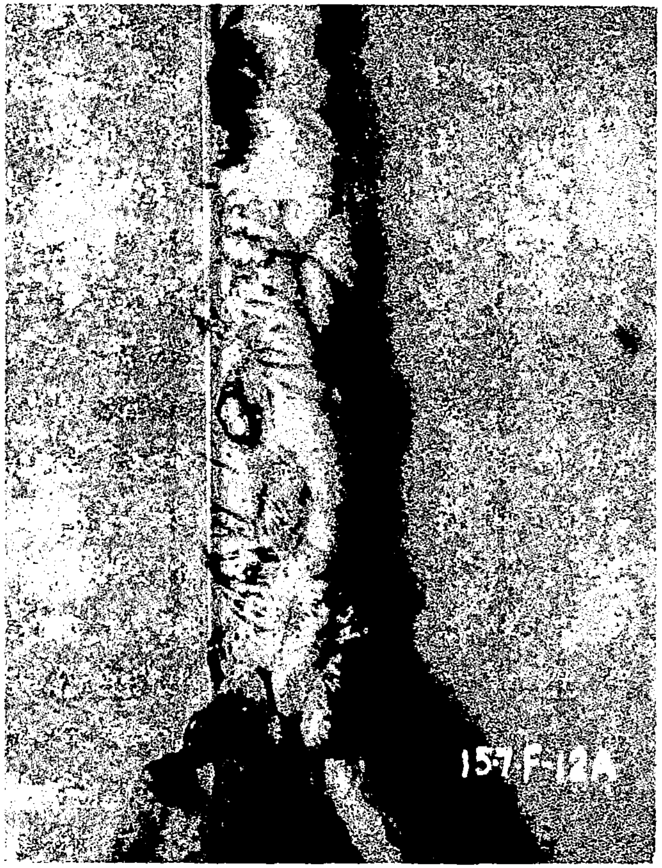


Figure 3.- Condition of rope shown in figure 2 after 7.5 seconds exposure to 4-ampere arc. Note melted spot on metal thimble and fused and scorched areas on surface of nylon.

Figure 4.- Sixty-cycle, 3-ampere arc along the surface of 13/16-inch nylon rope which had been treated with aquadag to give a resistance of 2000 ohms per cm. Length of specimen 15 cm. Exposure 0.01 sec.

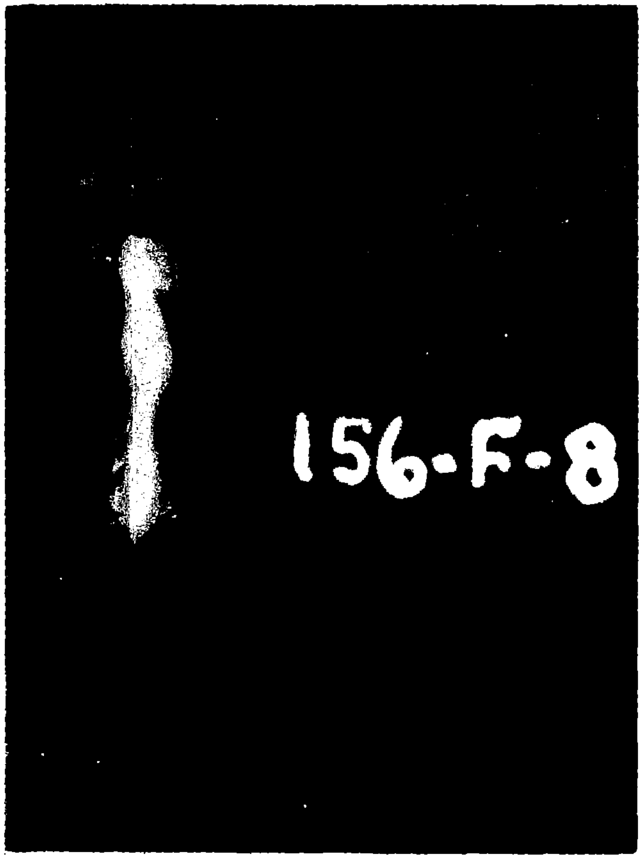


Figure 5.- Same trial as in figure 4, taken with camera at right angle.

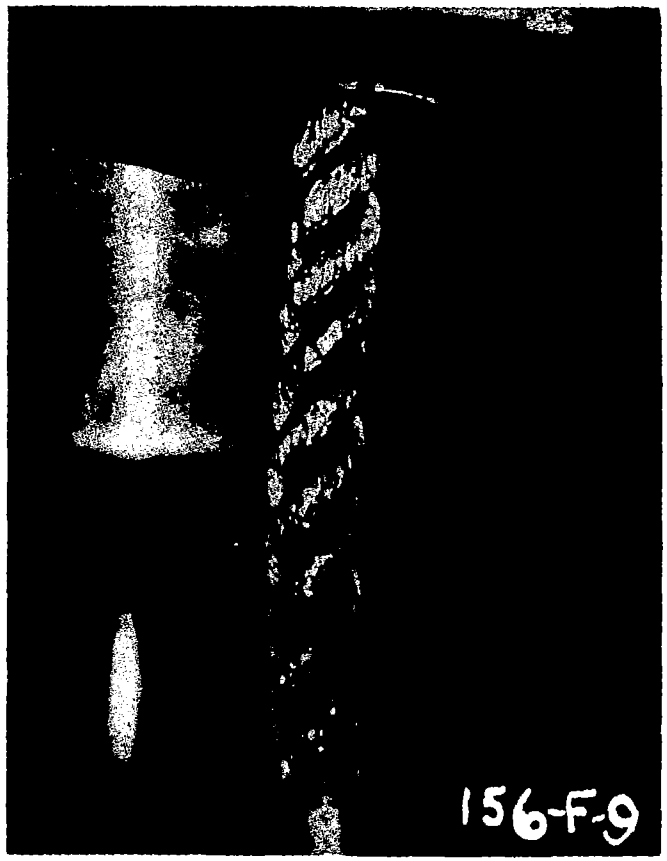


Figure 6.- Damage resulting from 10 seconds exposure to arc shown in figures 4 and 5. Note that surface fibers are fused to a homogeneous mass to a depth of about 0.5 mm.

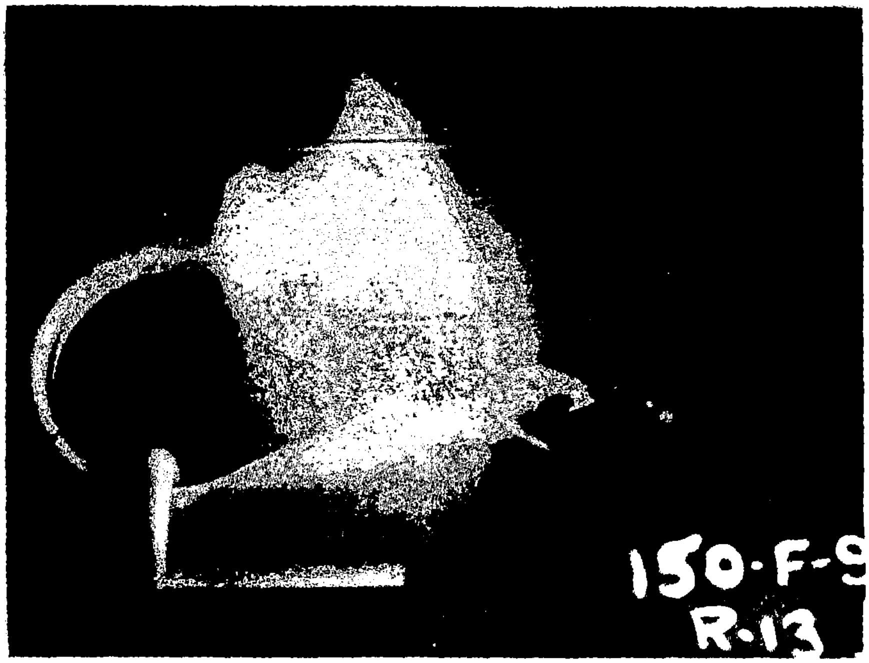


Figure 7.- 30-ampere d-c arc concentrated for 1 second between thimble and #10 copper wire. Camera shutter open during full duration of arc.

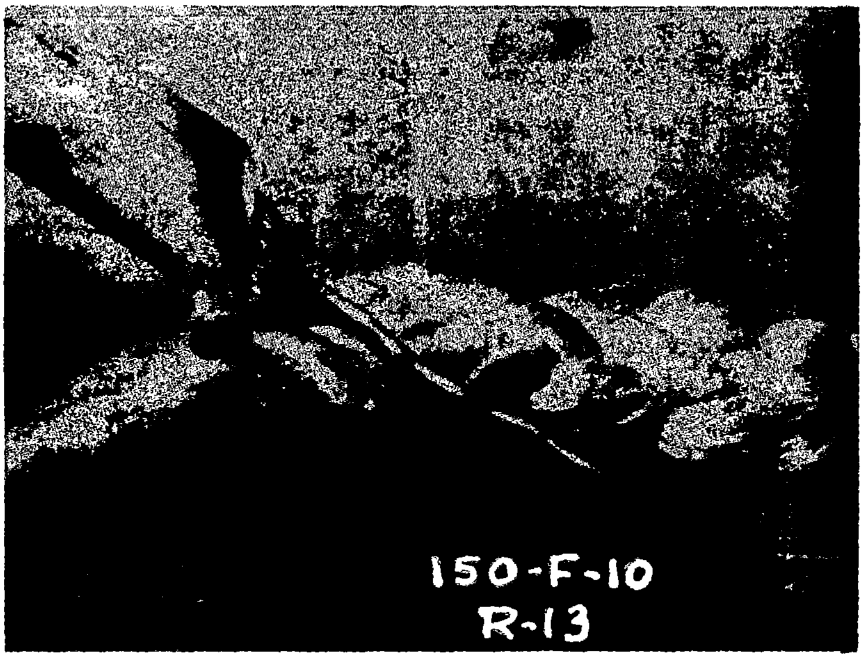


Figure 8.- Damage resulting from arc shown in figure 7. Surface is blackened and some fibers are fused but penetration is very slight.

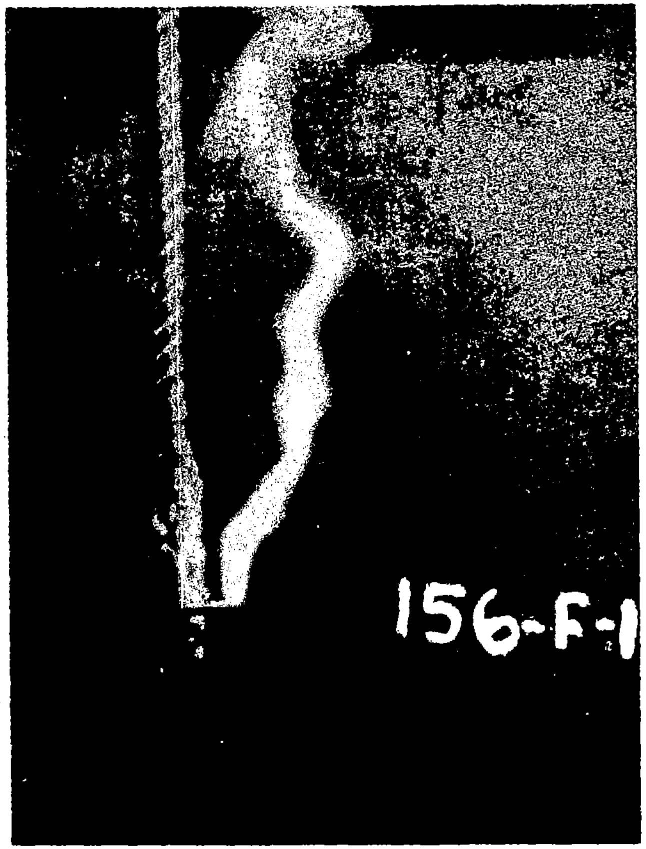


Figure 9.– Sixty-cycle, 4-ampere arc rising along dry, untreated 13/16-inch nylon rope; showing action of metal arcing ring in keeping discharge away from textile. No visible damage resulted.

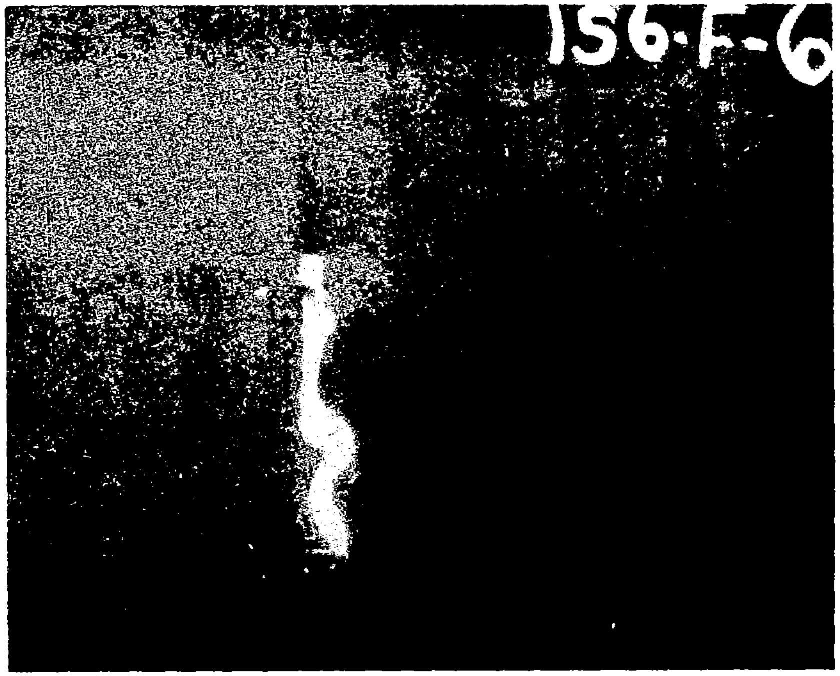
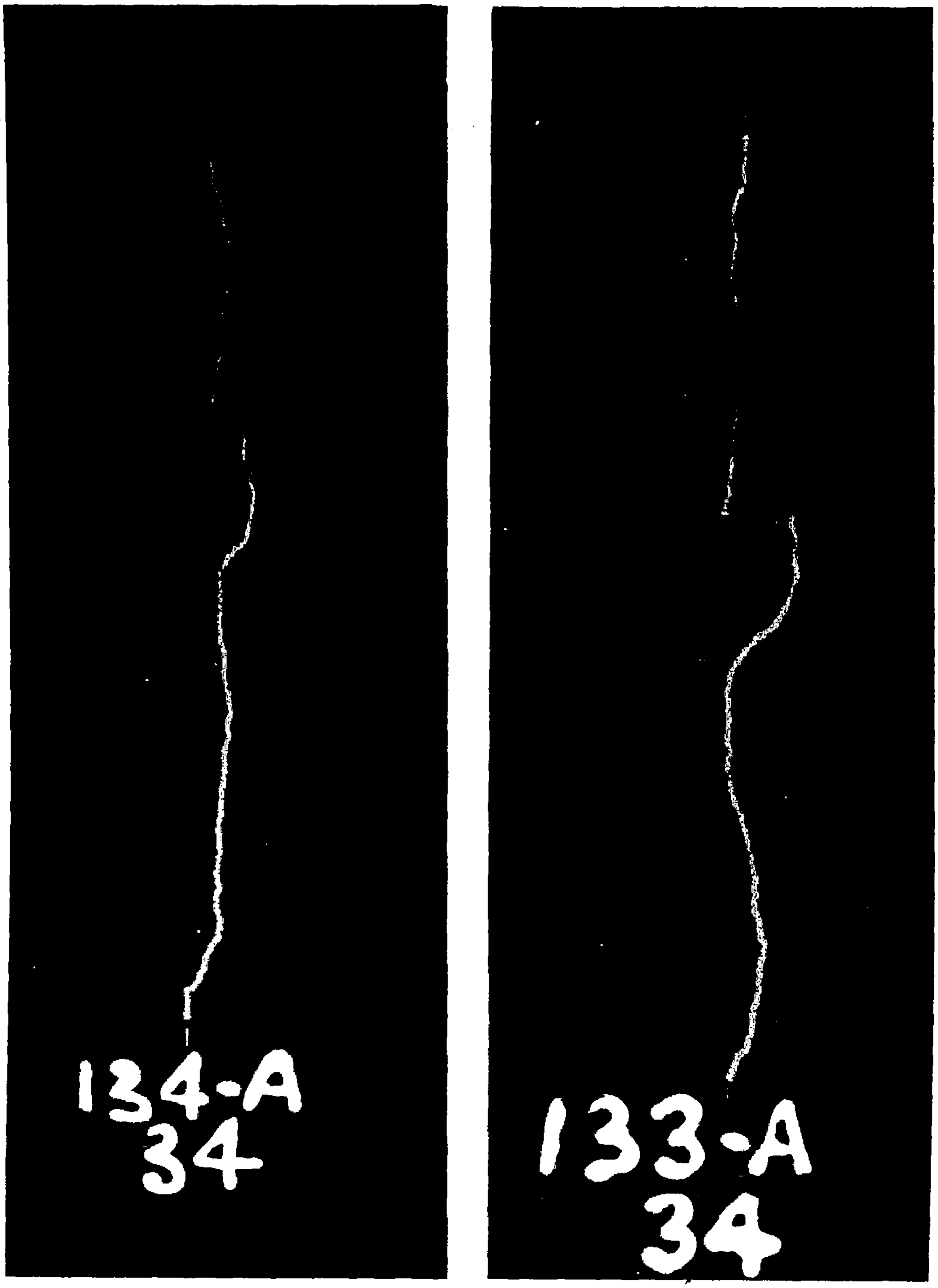


Figure 10.– Sixty-cycle, 3-ampere arc along aquadag-treated 13/16-inch nylon rope, showing action of metal arcing ring in keeping discharge away from rope at lower end.



(a) (b)

FIGURE 11.—*Surge discharge to model of tow.* (*a*) EAST CAMERA. (*b*) NORTH CAMERA. *This discharge strikes from the upper rod electrode to the metal towline and leaves by left wing tip of the towing plane to continue to the lower electrode. Distance between electrodes, 8 feet. The thin lines are the paraffined threads which supported the model.*

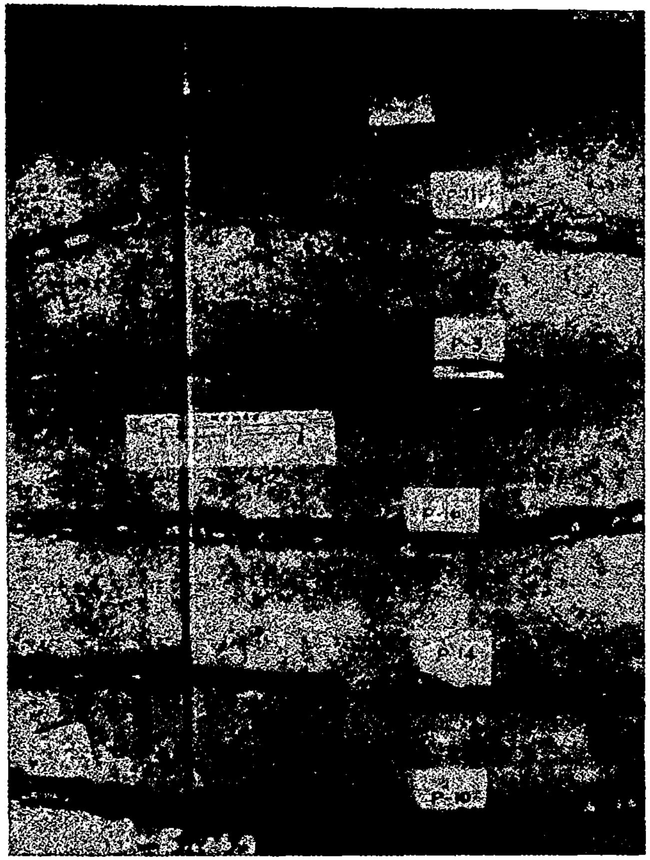


Figure 12.- Steel aircraft cable samples after test with 1000-ampere surge followed by 30-coulomb arc while under mechanical tension. Unprotected samples P-12, P-3, and P-14, respectively 1/16", 3/32", and 1/8" in diameter, all failed though tension applied was only 100 pounds. Samples P-11, P-16 and P-10 of same diameter respectively as the others and subjected to 600 pounds tension did not fail because protected by metal braid and thin layer of insulation.

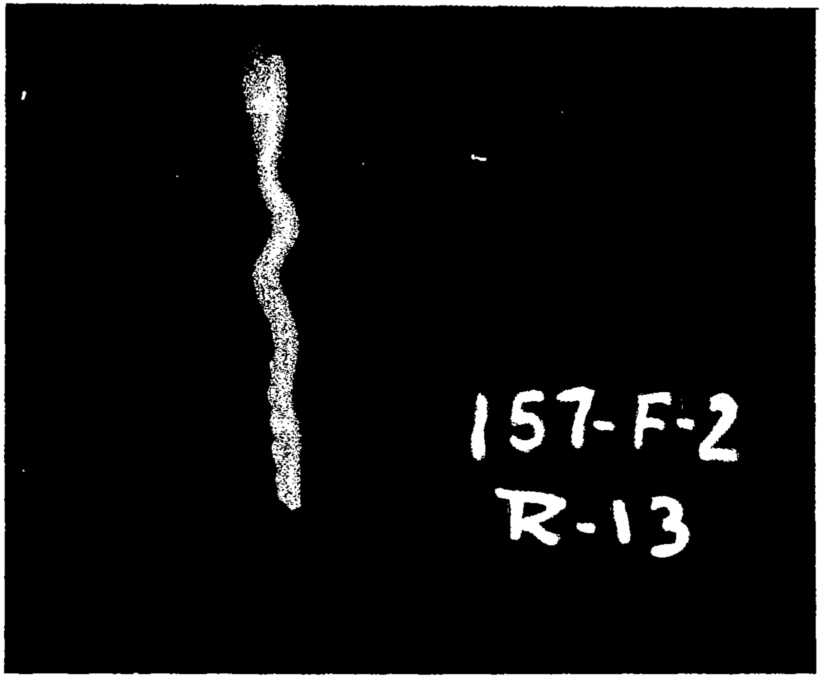


Figure 13.- A sixty-cycle, 3-ampere arc passing from a horizontal rod electrode (barely visible at the bottom) across a one-centimeter gap to the aquadag-treated rope and along the rope for 26 cm to an upper sleeve electrode.

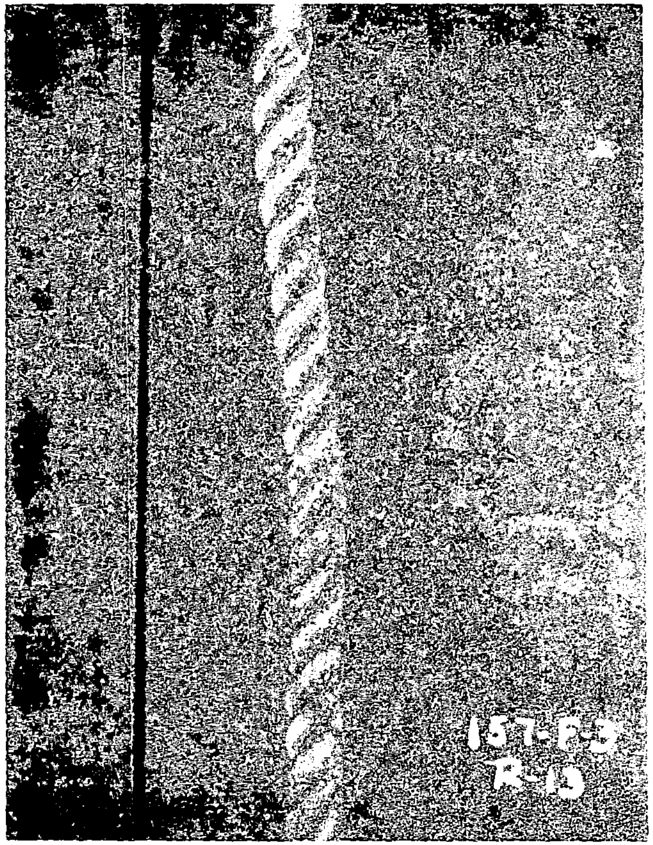


Figure 14.- Damage resulting from arc shown in figure 13, after arc had ceased and restruck three times for a total application of 14 seconds. The scorching and melting of the surface is confined to a thin layer and is not concentrated opposite the rod electrode.

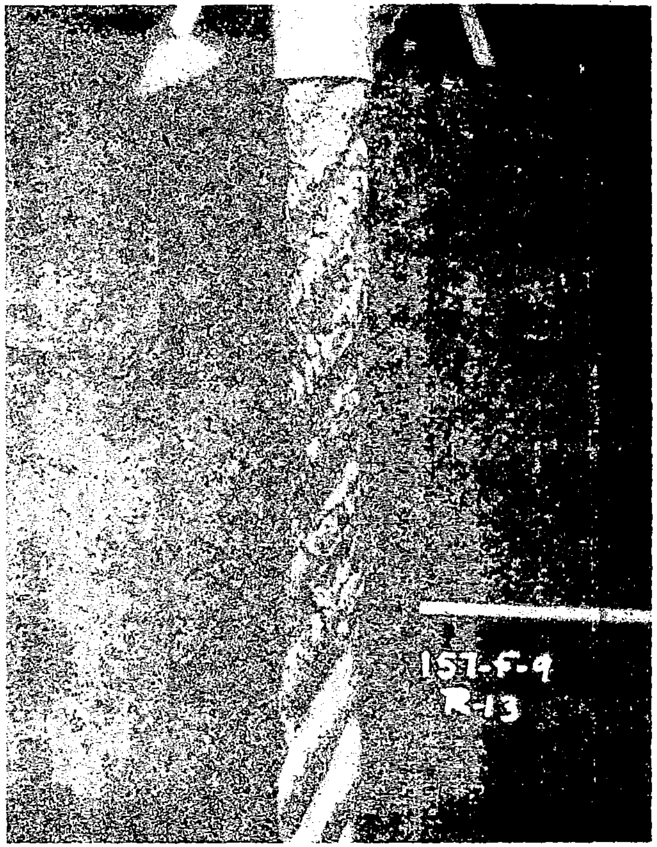


Figure 15.- Damage produced on 13/16-inch nylon rope, treated with aquadag so as to have 200 ohms per cm, after a 3-ampere a-c arc had struck and restruck over its surface 5 times from the rod electrode to the upper metal sleeve during a total exposure of 15 seconds.

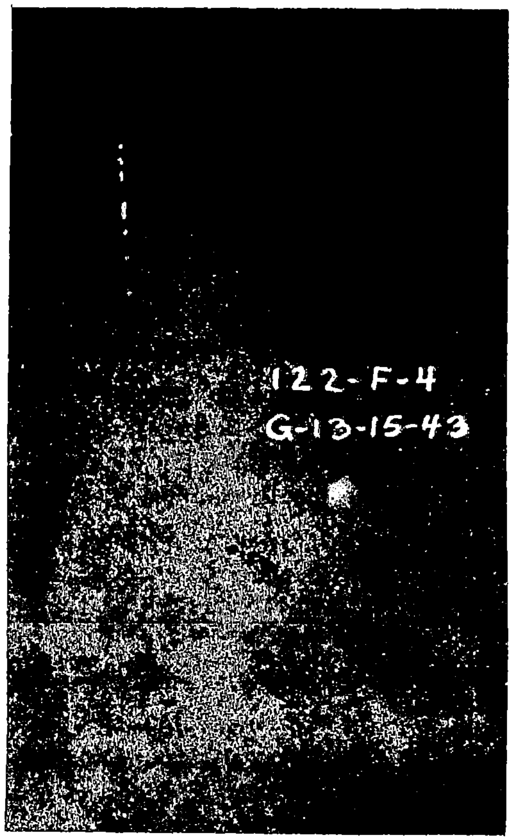


Figure 16.- Sparking and burning on a sample of 1/4-inch cotton sash cord 21 feet long. Cord had been dipped in tap water just before test. Picture taken by light of the arcs after 6 milliamperes direct current had passed through the cord for 2 minutes. After dissipating about 1 watt per cm for 5 minutes the cord broke under its own weight.

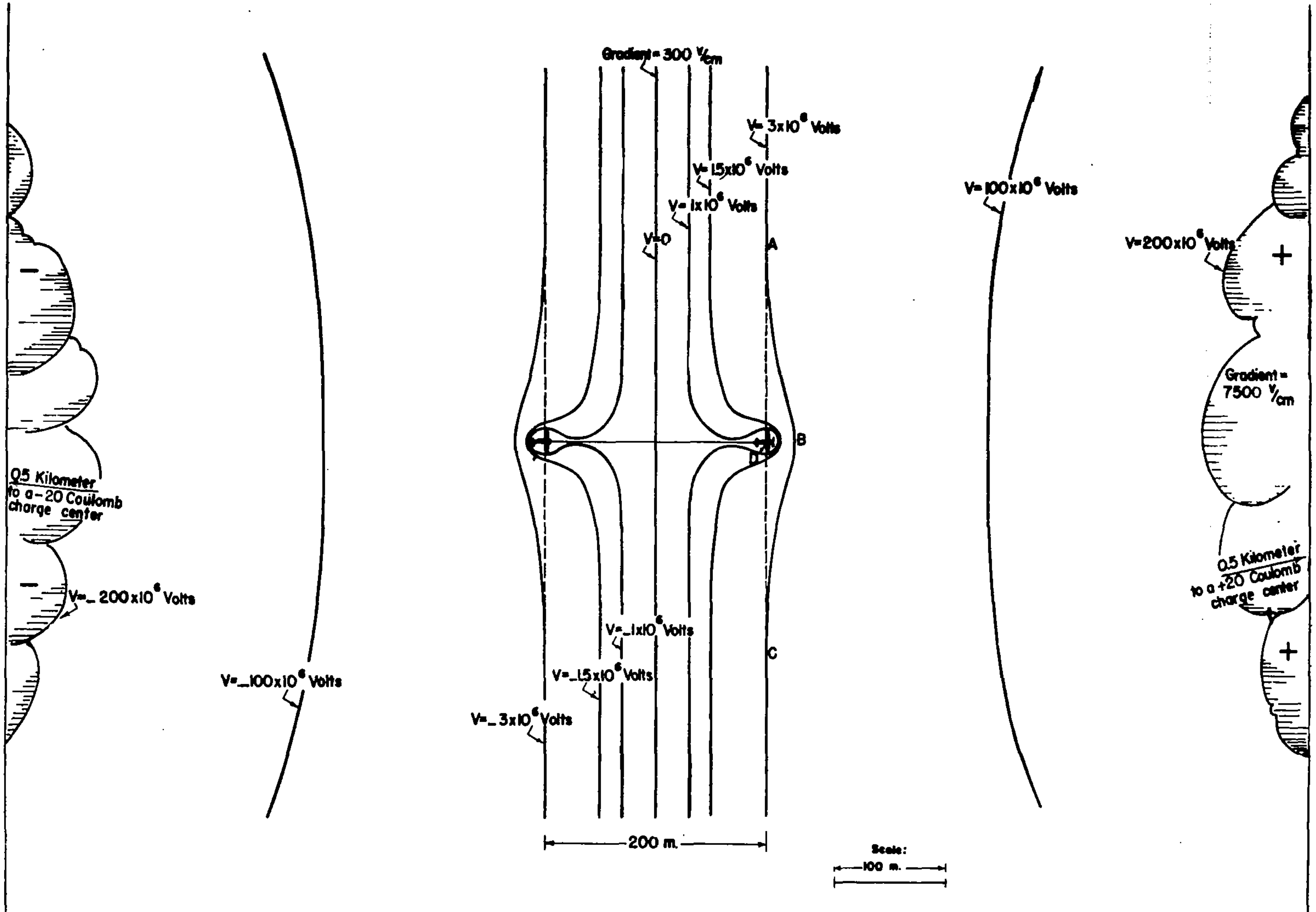


FIGURE 17.- DISTORTION OF ELECTRIC FIELD OF CLOUDS BY GLIDER TOW

NACA

Fig. 18

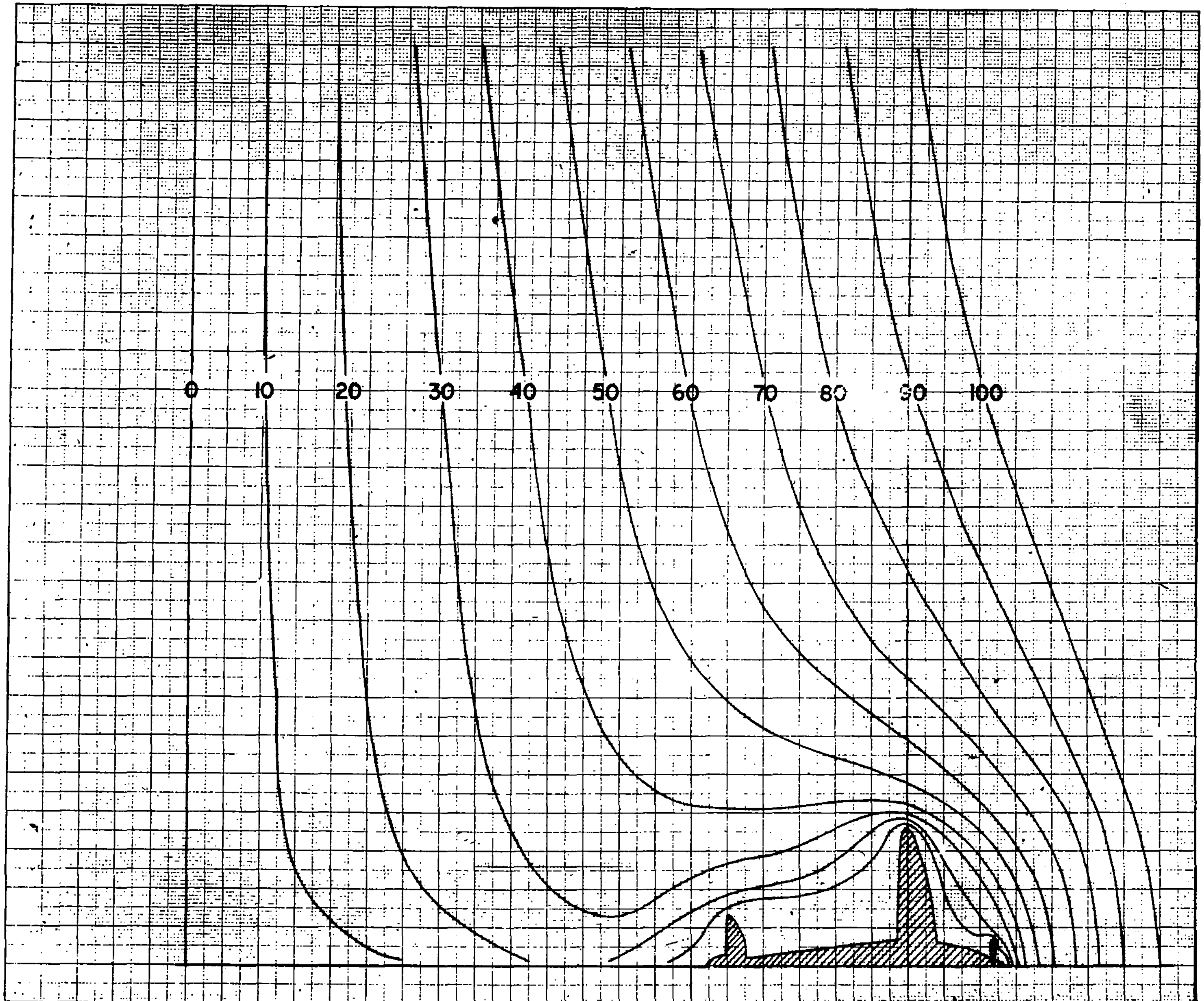


FIGURE 18.-ELECTRIC FIELD AROUND TOW PLANE

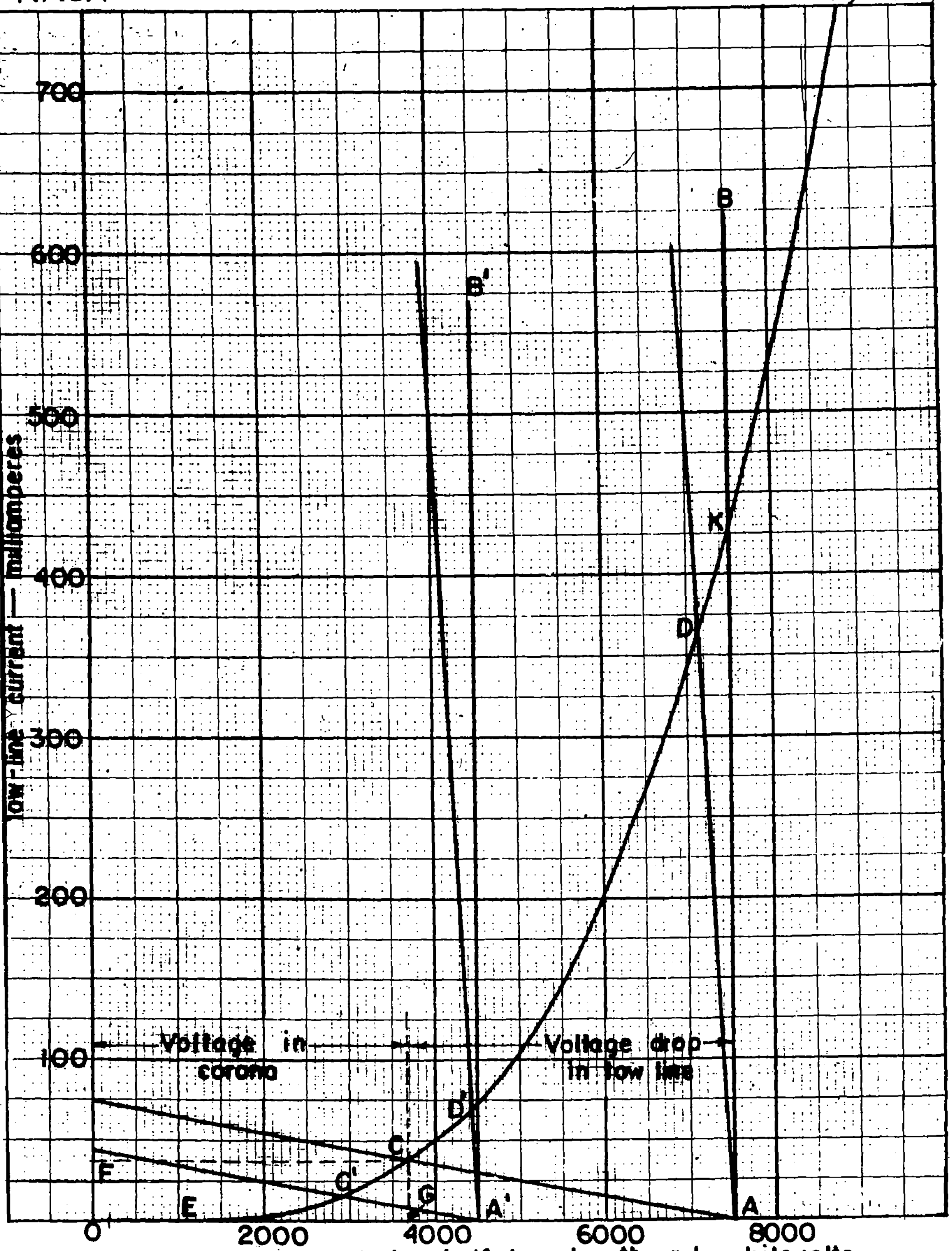
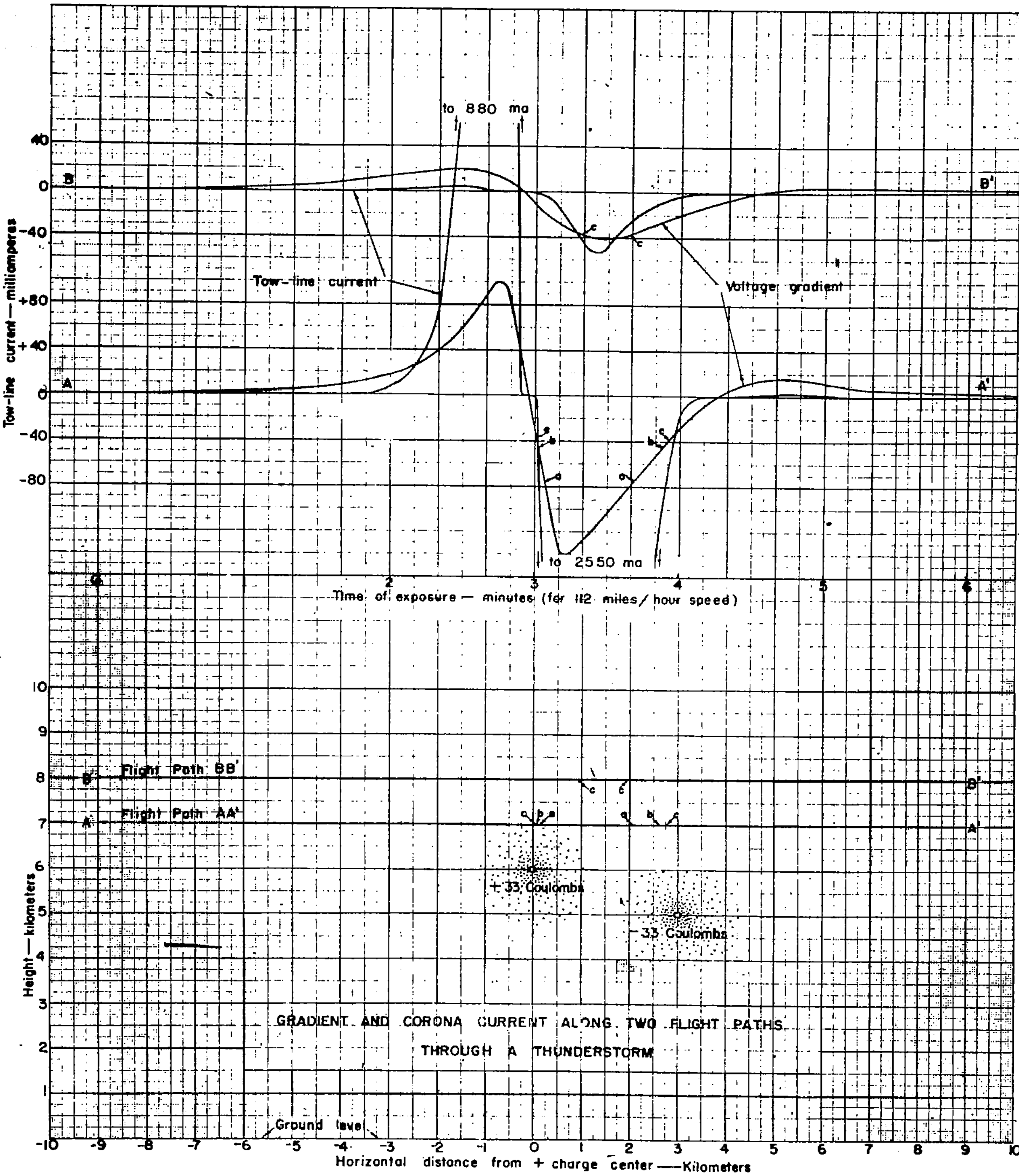

700
600
500
400
300
200
100
0
2000
4000
6000
8000
Tow-line current — milliamperes
Voltage spanned by half tow length $g_o l$ — kilovolts.
B
B'
K
D
D'
C
G'
G
F
E
A'
A
Voltage in corona
Voltage drop in tow line

FIGURE 19



GRADIENT AND CORONA CURRENT ALONG TWO FLIGHT PATHS THROUGH A THUNDERSTORM

FIGURE 20

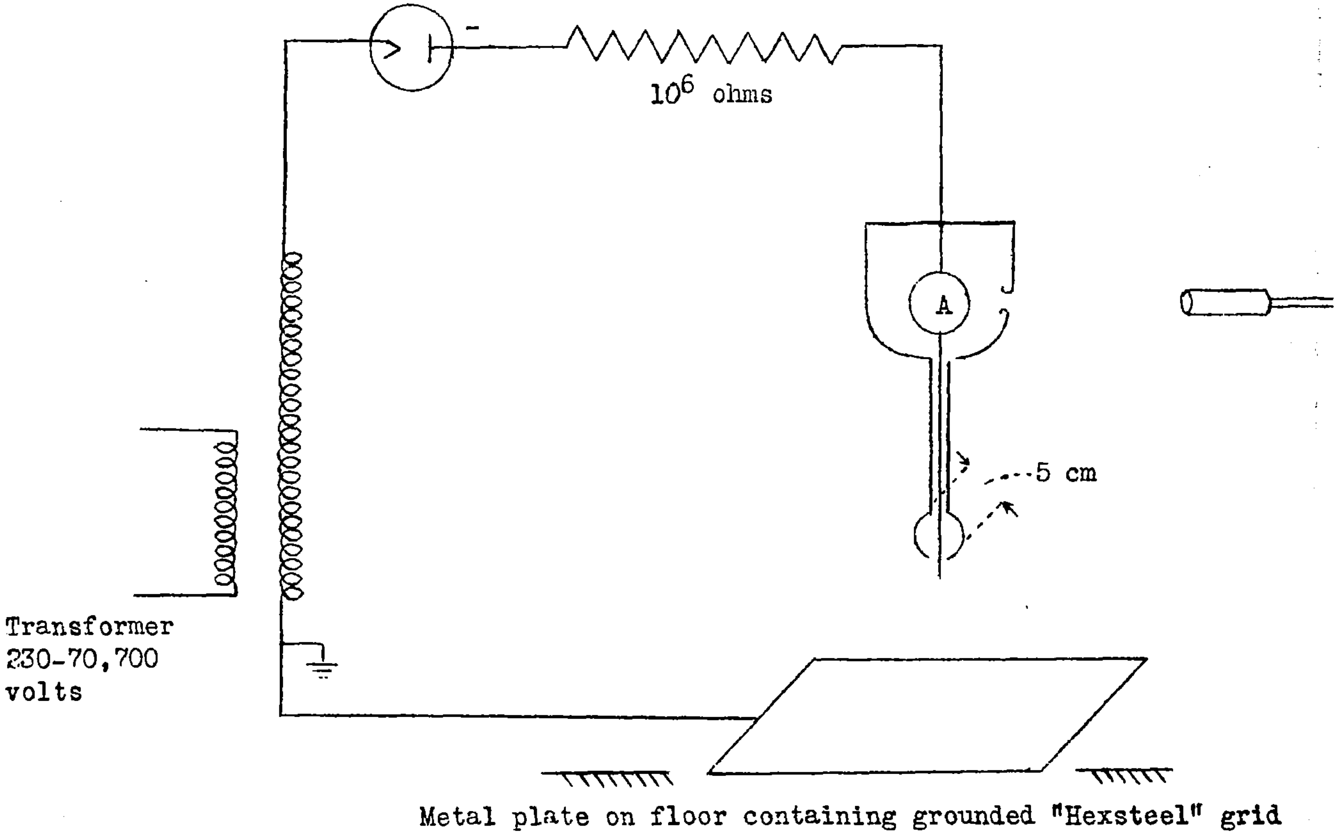
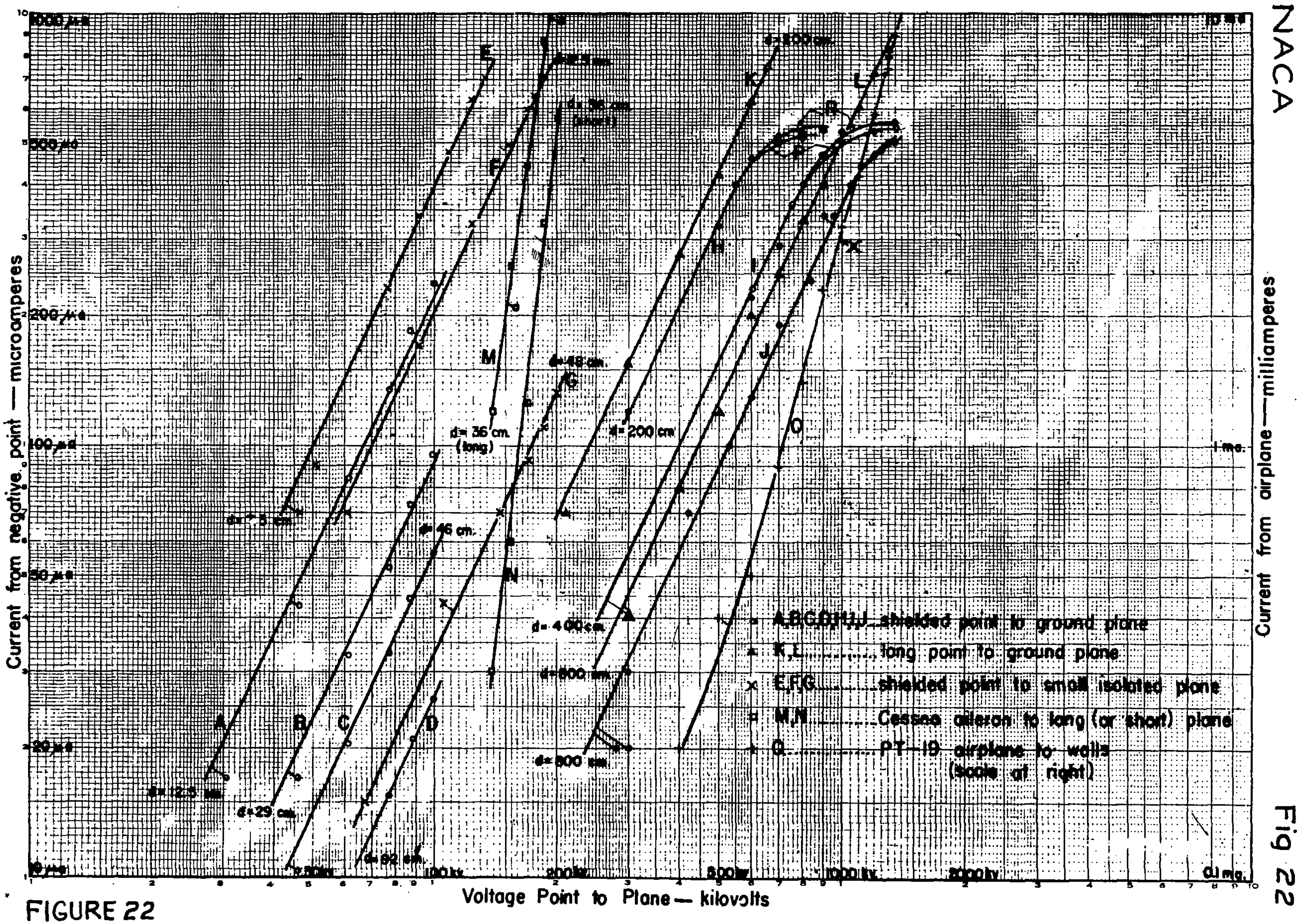


Figure 21.- Circuit for measurement of current in point-plane gap; plane at ground potential.



NACA
Fig 22
Current from negative point — microamperes
Current from airplane — milliamperes
Voltage Point to Plane — kilovolts
A,B,C,D,H,I,J ......shielded point to ground plane
K,L ....long point to ground plane
E,F,G ....shielded point to small isolated plane
M,N ....Cessna aileron to long (or short) plane
O ....PT-19 airplane to walls (scale at right)
d= 12.5 cm.
d=29 cm.
d=46 cm.
d=92 cm.
d= 36 cm. (long)
d=48 cm.
d=200 cm.
d= 400 cm.
d=600 cm.
d=800 cm.
100 kv
200 kv
500 kv
1000 kv
2000 kv
1000 μa
500 μa
200 μa
100 μa
50 μa
20 μa
10 μa
1 ma.
0.1 ma.

FIGURE 22

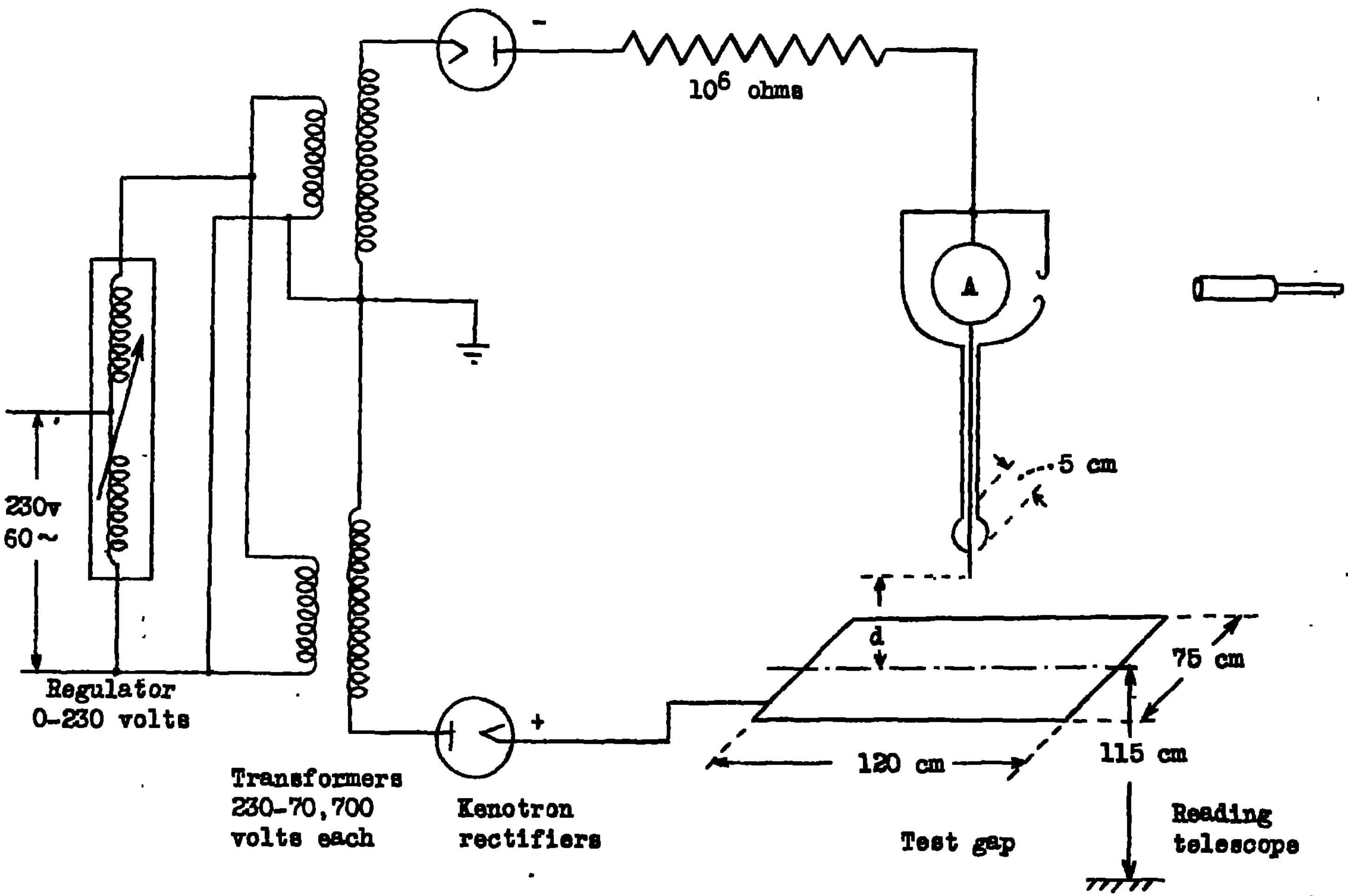


Figure 23.- Circuit for current measurement in point-plane gap ground at mid-point.

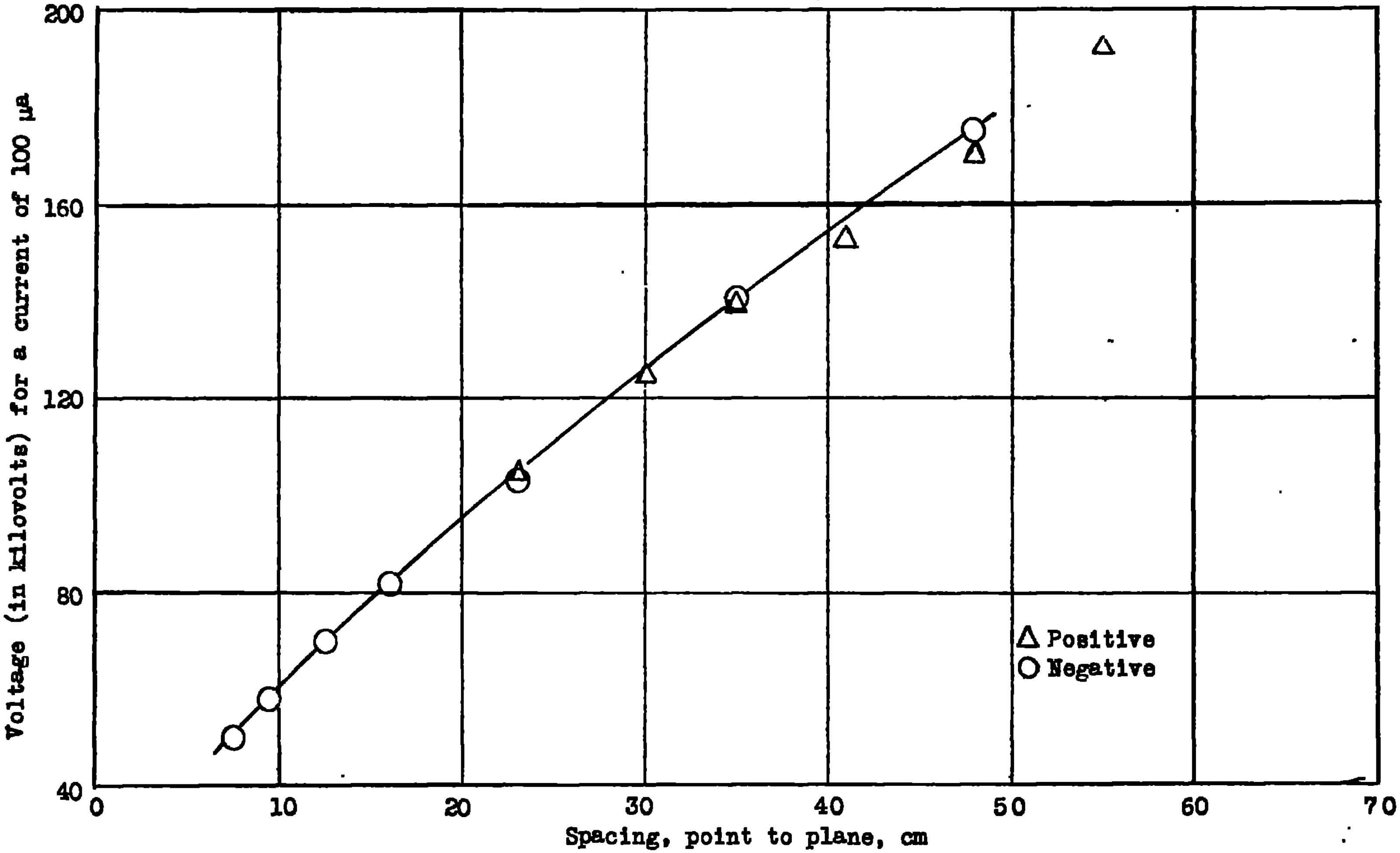


Figure 24.- Voltage (in kilovolts) for a current of 100 μa.

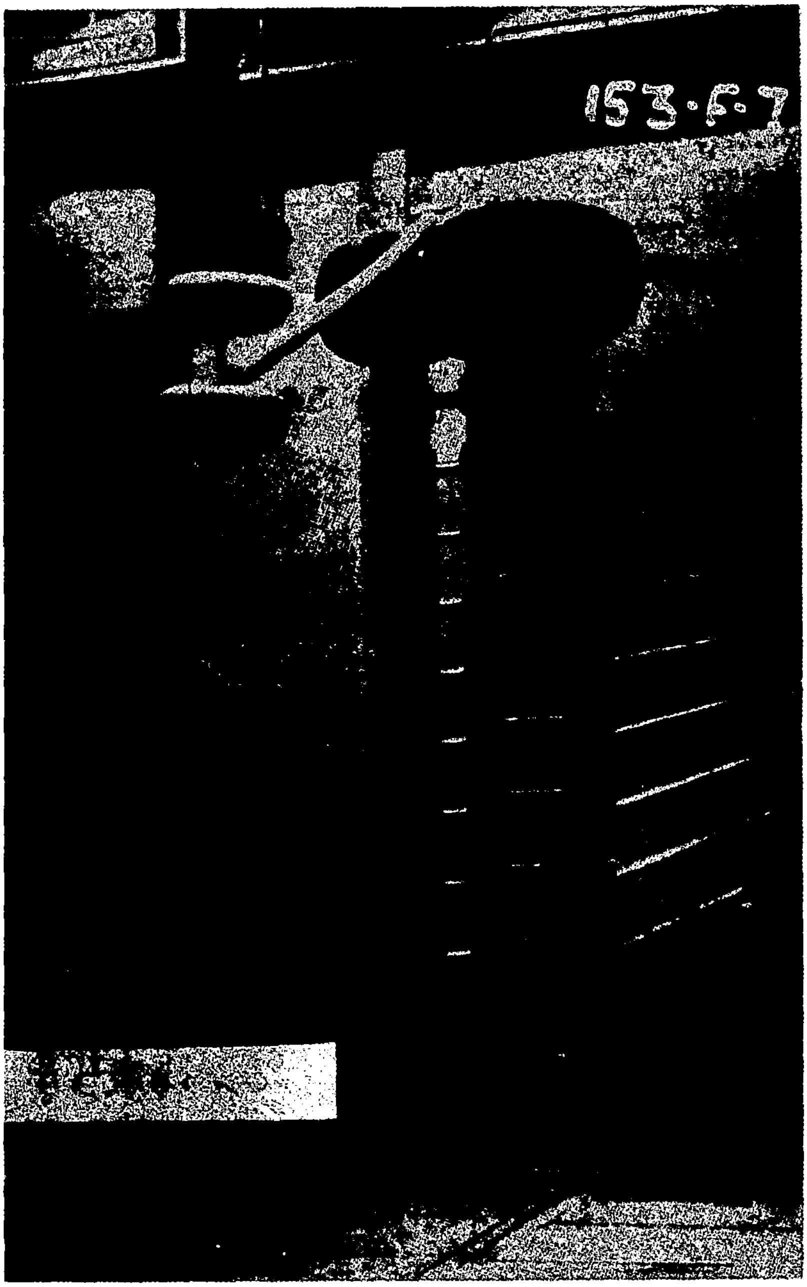


Figure 25.- The string of suspension insulators at the top of the photograph supports the two toroidal shields and the cylindrical shield below, which encloses the microammeter. The tube hanging down from this carries the polished 5-cm sphere from which the discharge point protrudes. The metal floor is the plane electrode. The lead, 6-inches in diameter and 42-feet long, connects the toroid with the 1.4-million volt X-ray generator. This lead is much foreshortened in the photograph.

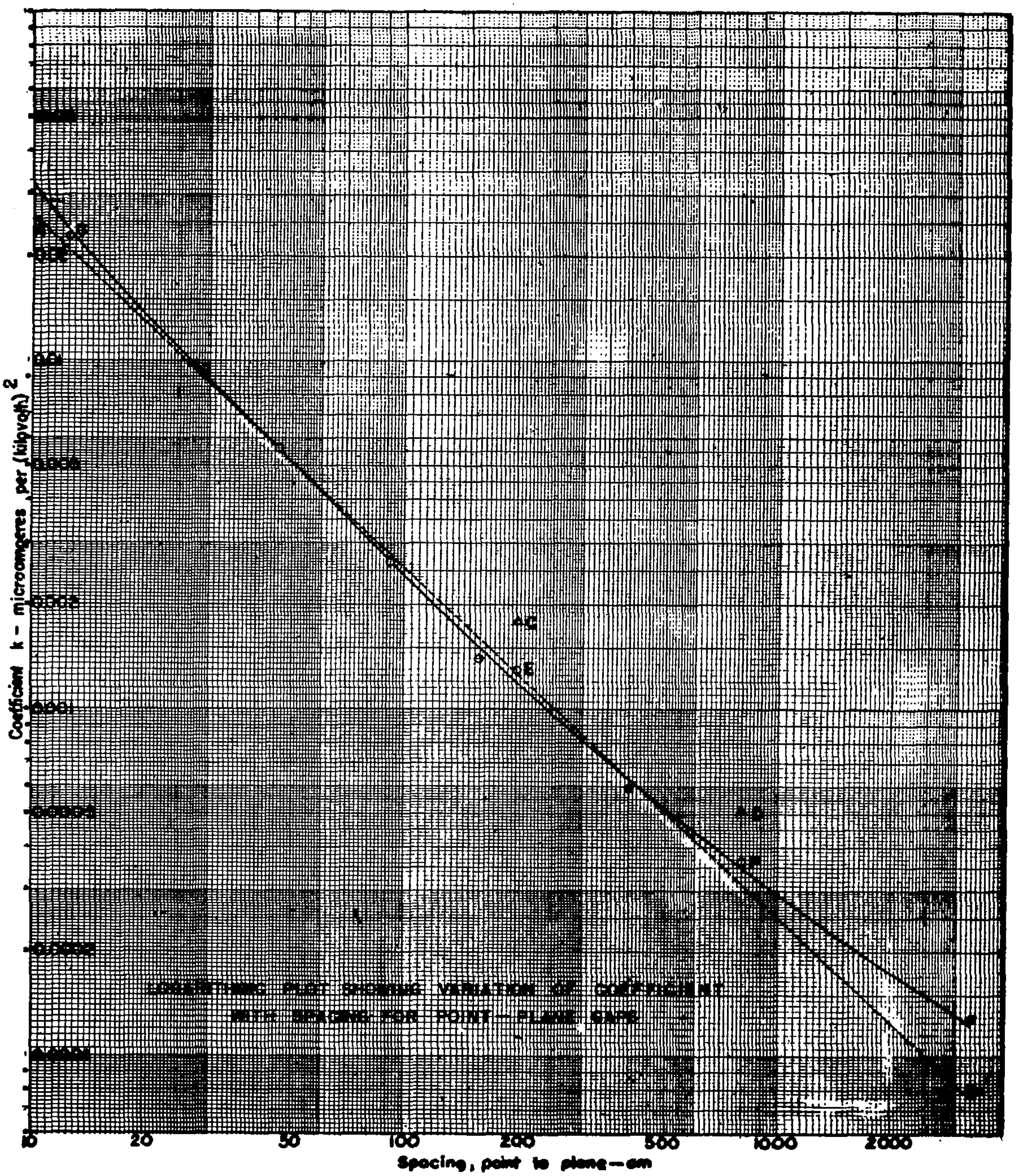

LOGARITHMIC PLOT SHOWING VARIATION OF COEFFICIENT
WITH SPACING FOR POINT—PLANE GAPS
Coefficient k - microamperes per (kilovolt)²
Spacing, point to plane—cm
10
20
50
100
200
500
1000
2000
0.001
AC
DC

FIGURE 26

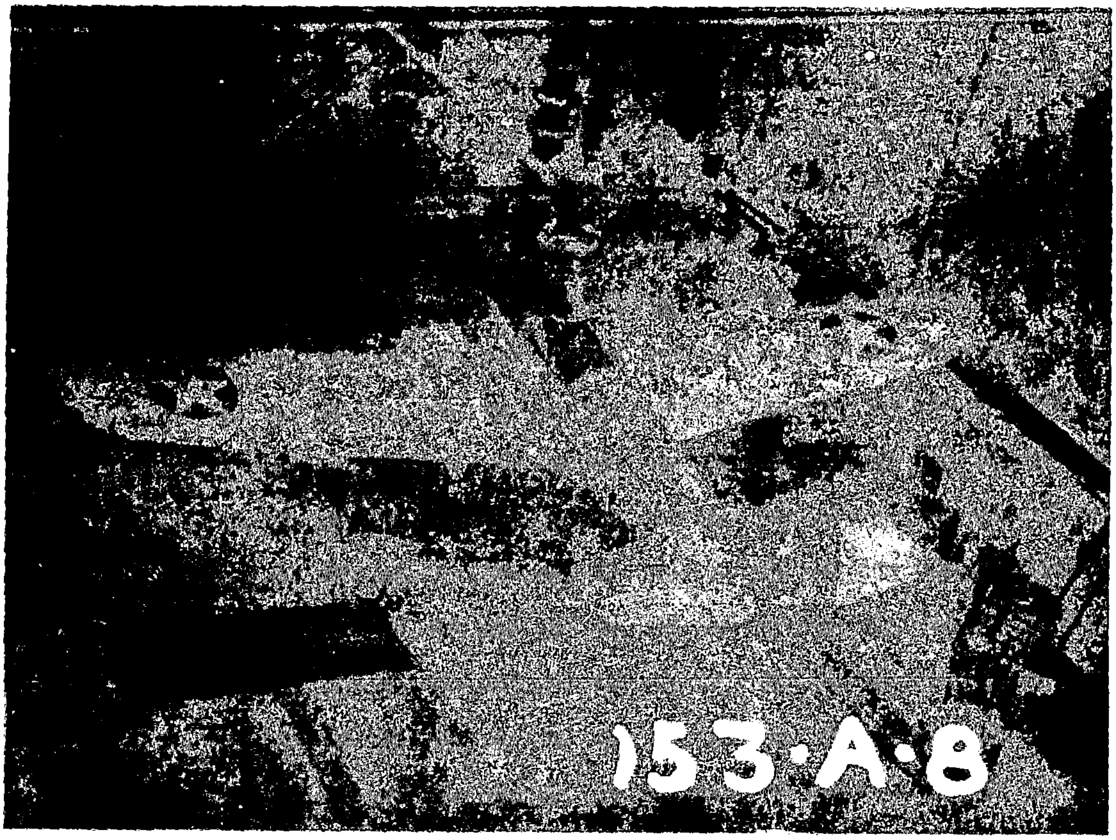


Figure 27.- Fairchild PT-19-A airplane suspended in High-Voltage Laboratory for corona measurements. The total corona current from the airplane was measured by a milliammeter enclosed in the cylindrical shield visible between the two toroidal shields

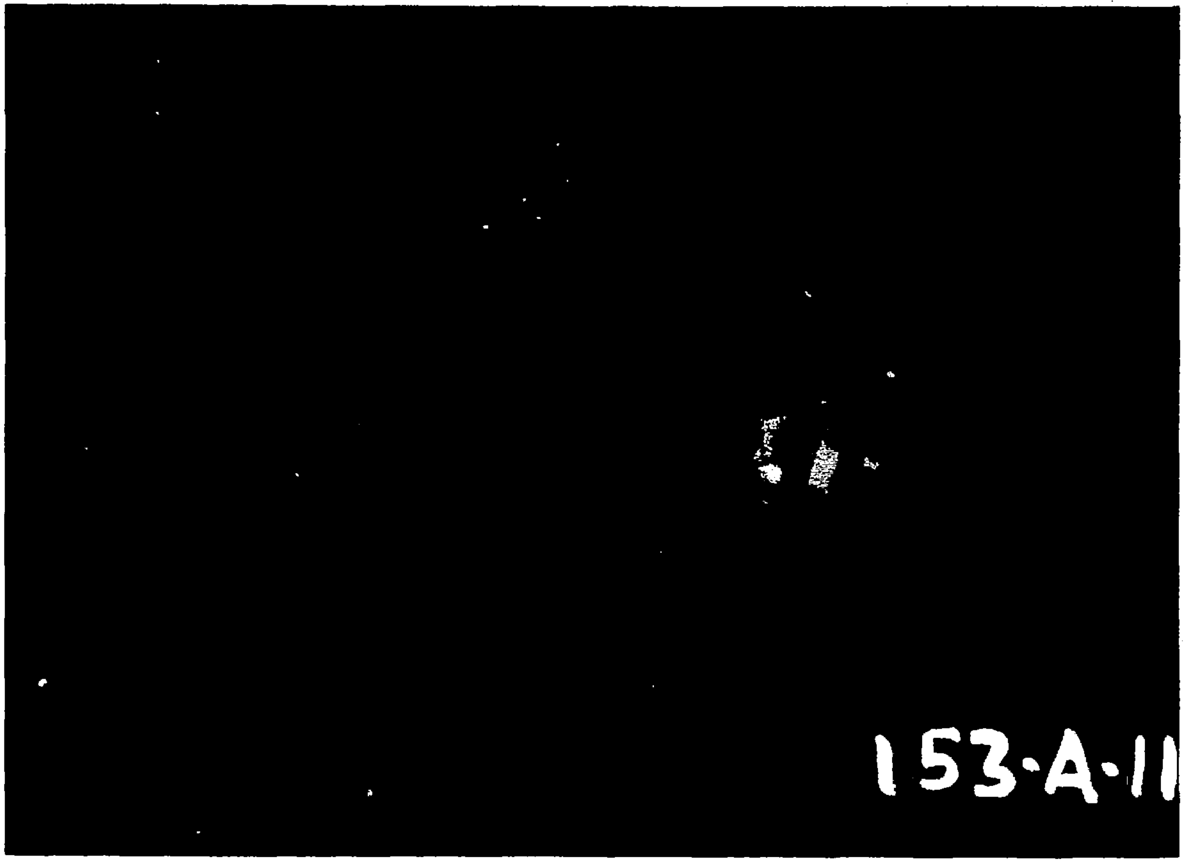


FIGURE 28.—*Corona discharge from Fairchild PT–19–A airplane when charged to —1,200,000 volts. The spreading of the spots is the result of a slight swinging of the craft by air currents during the course of the 10-minute exposure.*

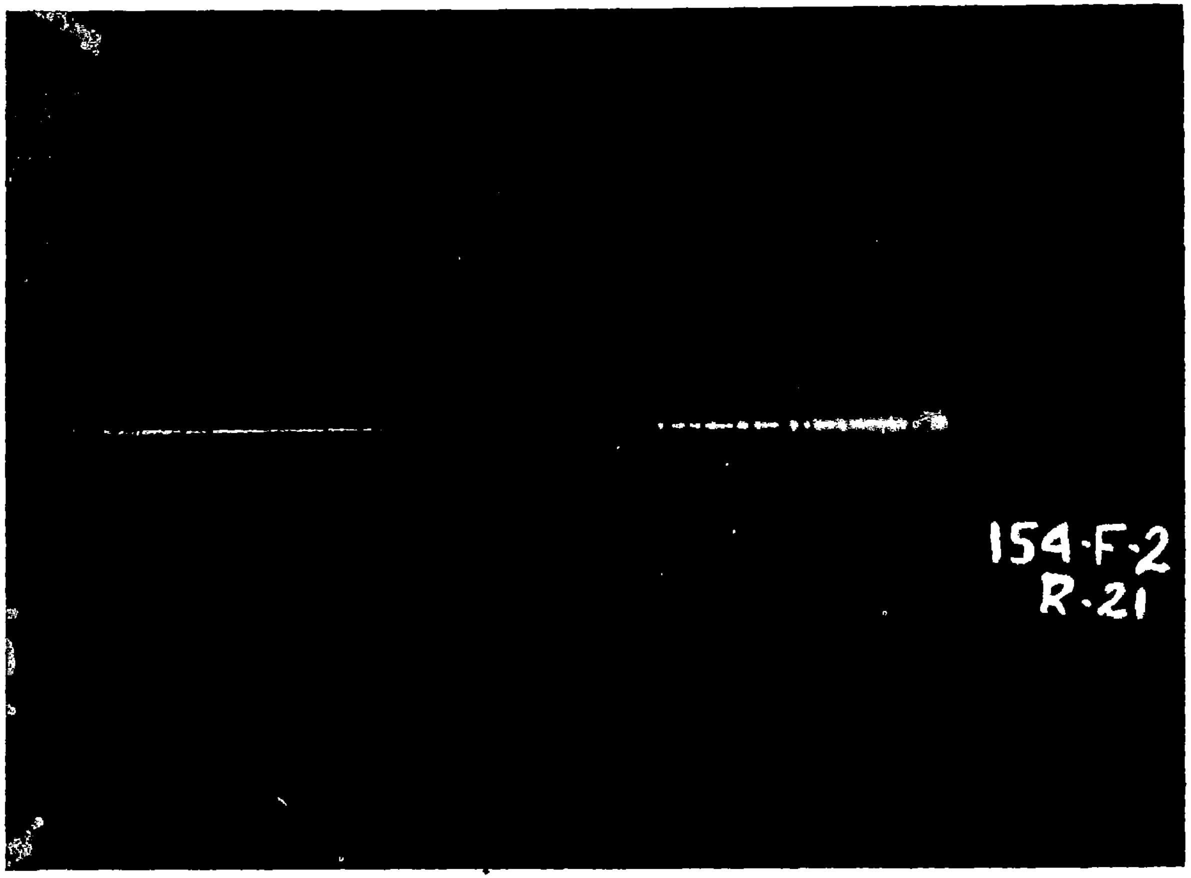


FIGURE 29.—*Corona discharge from fine (No. 36) wire stretched between two 1.6-cm. spheres and placed in electric field between two large metal plates perpendicular to the wire. Plates were charged to +70,000 volts at the right and —70,000 volts at the left. Note beaded character of corona from induced negatively charged end, and the smooth positive glow. Exposure 15 minutes at f4.5 Eastman Tri X Pan.*

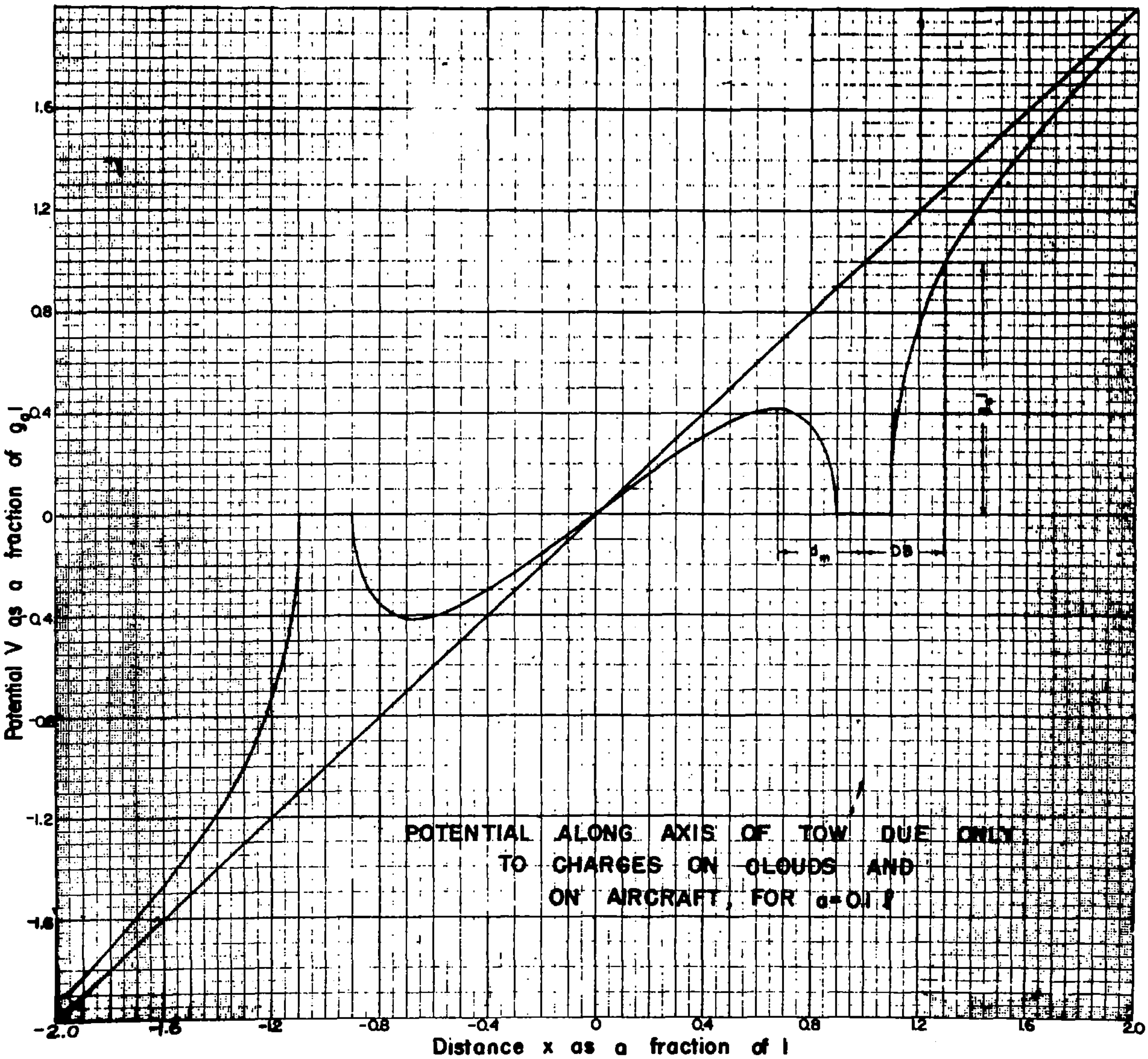

1.6
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
-1.6
Potential V as a fraction of $g_0 l$
-2.0
-1.6
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
1.6
2.0
Distance x as a fraction of l
d_m
0.8
POTENTIAL ALONG AXIS OF TOW DUE ONLY TO CHARGES ON CLOUDS AND ON AIRCRAFT, FOR a = 0.1 l

FIGURE 30

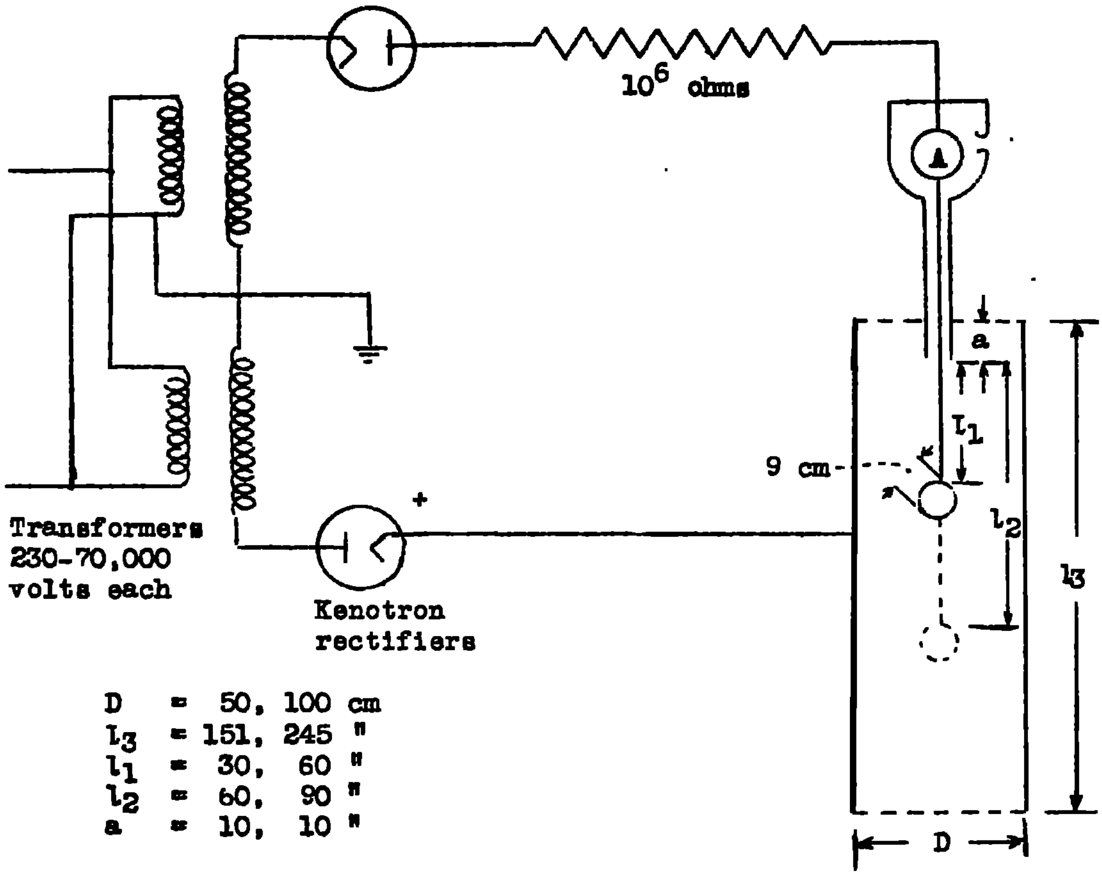


Figure 31.- Arrangement for measurement of d-c.corona current from wires.

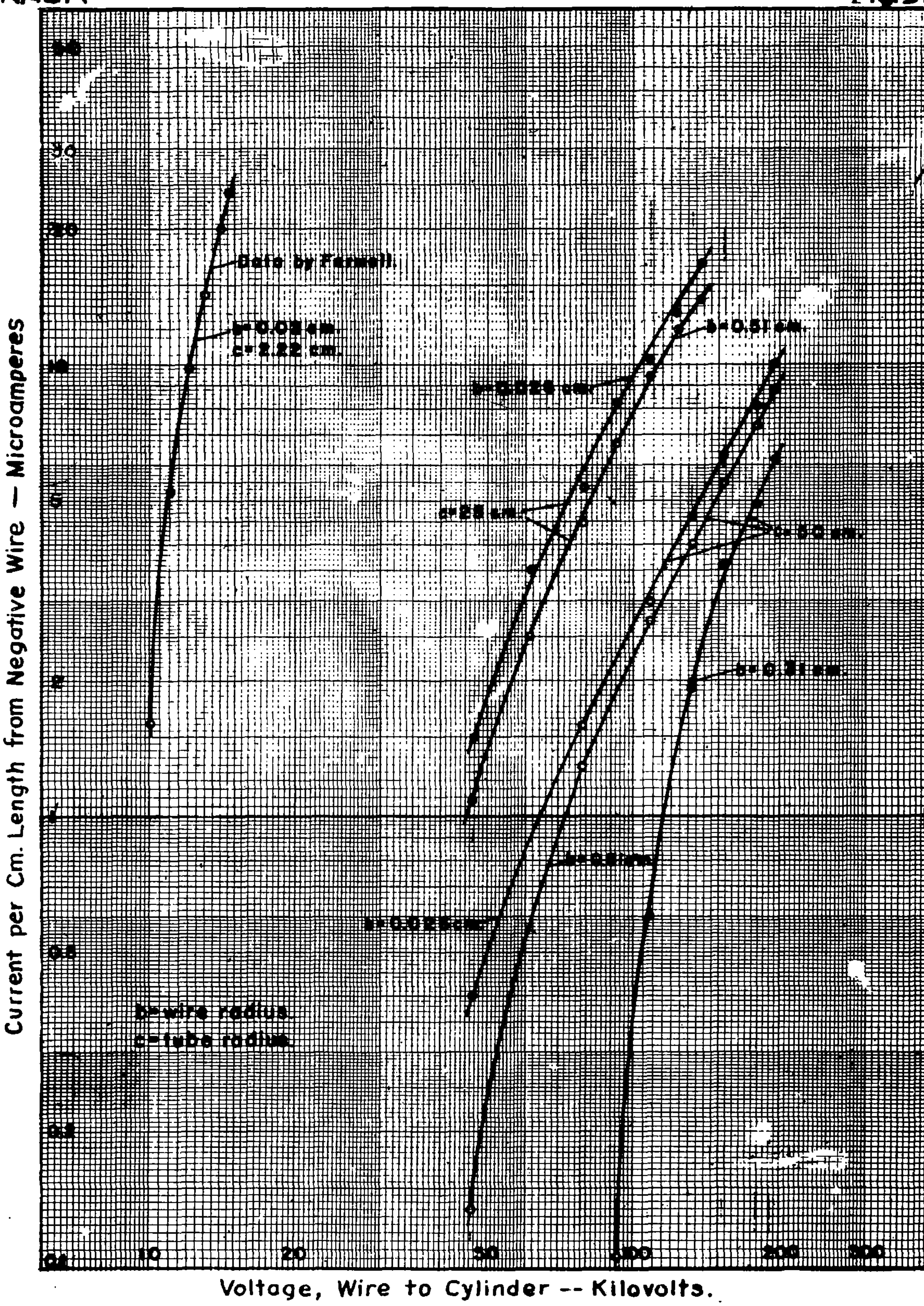

Current per Cm. Length from Negative Wire — Microamperes
Data by Farwell
b=0.02 cm.
c=2.22 cm.
b=0.51 cm.
b=0.025 cm.
c=25 cm.
c=50 cm.
b=0.51 cm.
b=0.51 cm.
b=0.025 cm.
b=wire radius
c=tube radius
10
20
100
200
Voltage, Wire to Cylinder -- Kilovolts.

FIGURE 32